Sustainable Energy Storage
Final Design Review (FDR)

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Statement of Disclaimer

Abstract
This Final Design Review document covers the work we, students at California Polytechnic State University – San Luis Obispo, have performed in collaboration with Mr. Harish Bhutani and Dr. Mohammad Noori. The project's intent is to create an energy storage system for off-grid and developing region applications using alternative technologies to lithium-ion battery storage. We plan to manufacture and assemble a scale model of the energy storage system to prove effectiveness and practicality. This system will store enough energy to power basic appliances and essential devices for a house or community. The chosen design direction will be a flywheel, as it is very energy dense and is less complex than other options. The following will outline the entire design process, including the ideas we created, the design challenges, and the testing of our physical build. To meet climate change goals set around the globe, our world needs to head towards a more sustainable future, and the energy sector is no exception. This project aims to help with the research and design of this new field and present a final product that will have a meaningful impact on our world.

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1 Introduction

Our team's main intention is to create a viable alternative to battery storage technology that is environmentally sound and economically feasible to implement, giving areas without grid infrastructure the ability to power and use devices outside of typical energy generation periods. Our team consists of four senior engineering students – three mechanical engineers and one computer engineer. Alyse Coonce is the project manager and will be staying at Cal Poly for the upcoming academic year to pursue her Blended Bachelor and Master of Science (BMS) in Mechanical Engineering. Jake Grillo and Jack Linchey are both mechanical engineers and are the main manufacturers of this project. After completing his BS in mechanical engineering this spring, Jake is pursuing a Master's degree in Renewable Energy from KTH Royal Institute of Technology. Jack will also be graduating at the end of this quarter and will be going directly into industry. Nick Schnorr, as a computer engineering major, is our motor and control system expert; at the end of December 2021, he will complete his BMS in Computer Science.

With our collective educations and passions, we understand the need for renewable energy and believe there is an exigency for improvement in sustainable energy storage. Senior Project advisor Dr. Mohammed Noori proposed the concept of creating a project centered around the term "Sustainability", which was to be funded by Cal Poly alumnus Mr. Harish Bhutani. To accomplish the goal of a final product that will have a meaningful impact on our world, our team targeted the growing market of energy storage solutions with a specific intent on the developing regions of the world.

For the remainder of this document, Chapter 2 covers the preliminary research of four alternative storage solutions with comparisons across each. Our project objective is found in Chapter 3, addressing the needs, wants, and constraints of our design. Chapter 4 and 5 cover the individual conceptual designs and finalized designs of the system respectively. The manufacturing of our subassemblies and system testing processes are discussed in Chapters 6 and 7 respectively. Chapter 8 covers our project management documentation and Chapter 9 rounds out the document with a discussion of suggested next steps and project conclusion.

2 Background

There are many ways to sustainably store energy, but for our project application, time, and funding, we needed to identify which energy storage systems could be the most realistic given the constraints. Storage systems can be broken into two different categories: those that deliver precise amounts of electricity over a short duration of time (capacitors, batteries, flywheels, etc.), and those that take more time to boot up but can supply hundreds of megawatts for extended hours (compressed air, pumped hydropower, etc.) (Bindrah). For the application pertaining to our specific project, which is on the smaller residential scale as opposed to a larger industrial scale, massive amounts of energy are not required. Instead, homeowners desire a small system that can deliver a reasonable amount of energy for a few hours.

2.1 Lithium-Ion Batteries

Our world currently relies heavily on these chemical batteries to power everyday products. When battery storage systems became more commercially available in the early 2000's, most US systems were using nickel and sodium-based chemistries. Since 2011, however, there has been a massive shift towards the use of lithium-ion batteries (U.S. EIA). Lithium-ion batteries are comprised of two electrodes; one is positively charged and contains lithium, and the other is negatively charged and is typically made of graphite (PNNL). When electrons flow through the wire connecting the two electrodes, electricity is then generated.

Lithium-ion batteries have many advantageous properties, such as their long-life cycle, high efficiency for charging and discharge, and extremely low maintenance during operation (Lu). However, these chemical batteries still introduce their fair share of problematic effects. Lithium-ion batteries have very specific temperature and voltage operating windows, so a battery management system, complete with sensors, controls, and actuators, is necessary to ensure the battery operates safely (Lu). To improve the battery's safety, performance, and voltage, additional materials like cobalt, nickel, and manganese are often incorporated into the battery cells. Unfortunately, these metals are considered toxic heavy metals; pollution is associated with the mining of these metals, and there is also the effect on child labor in cobalt mines in the Democratic Republic of Congo (Rapier). In addition, lithium-ion batteries are recycled at a rate below 5% (Rapier), which can be attributed to a lack of recycle processing centers. Due to the limited resources of lithium ion and recycling centers, the transportation of these batteries has an increased global warming potential (Boyden).

Lithium-ion batteries now represent more than 90% of the installed power and energy capacity within the U.S. for large-scale energy storage applications (U.S. EIA). While the US Energy Information Administration, EIA, was unable to definitely collect chemistry data around small-scale battery installations, such as within the residential sector, it can be surmised that lithium-based batteries would still greatly outnumber other battery types (U.S. EIA). As more renewable sources become available to the average consumer, the demand for storing clean energy for later use increases. With the mining of rare earth metals, unregulated manufacturing, and hazardous recycling process at the end of life, chemical batteries could cost the environment a great deal.

2.2 Customer Research

In focusing on off-grid users who would require a storage system to supply energy beyond the peak energy generation period, tiny house homeowners became a representative case study of power usage for the intended user. Tiny houses generally have the modern amenities of appliances and lighting systems that a modern house may have but scaled down to a cabin or cottage. Owners who have opted to install solar arrays either upon the building's roof or as a field unit have selected 6kWh to 7kWh storage systems based on usage of around 3.5 to 4kWh per day (Rettenwender). Additionally, 40% of the daily usage is attributed to refrigeration and HVAC equipment in the tiny houses profiled for Rettenwender's study. Similar to tiny houses are the applications in developing regions and off-grid housing, where energy usage per capita is similar, but the main infrastructure of a tied-in grid would be absent. The system is intended to work alone but can be coupled with the grid if necessary. These groups are differentiated by what the power may be drawn for, with off-grid and developing region uses drawing for life-critical applications such as refrigeration or heat. Though a tiny house application will use these as well, it may be coupled with usage for lighting and creature comforts like high-end appliances.

We expect the main product to supply the power to our system to be solar panels. Based on research into solar panel capabilities, most standard panels produce a range of power from 250 W to 400 W (Aggarwal). This varies from company to company, but the bulk of these panels are only about 18% efficient. Furthermore, this implies that only 18% of the energy from the sun that hits the panel is converted to electrical energy, when the sun is directly facing the panel, (Aggarwal). For the purposes of our study, we will assume solar panels to average 300 Watts per panel at peak performance.

2.3 General Energy Storage Research

The basic forms of stored energy are electrical, chemical, mechanical, and thermal energy, which respectively can then be divided into subgroups and is discussed further in sections 3.2 – 3.5 of the report. Each energy storage system has its own characteristics, application areas, disadvantages and advantages associated with it. One way to visualize these relationships amongst storage technologies is by looking at a Ragone chart, shown below in Figure 1 (Droege).

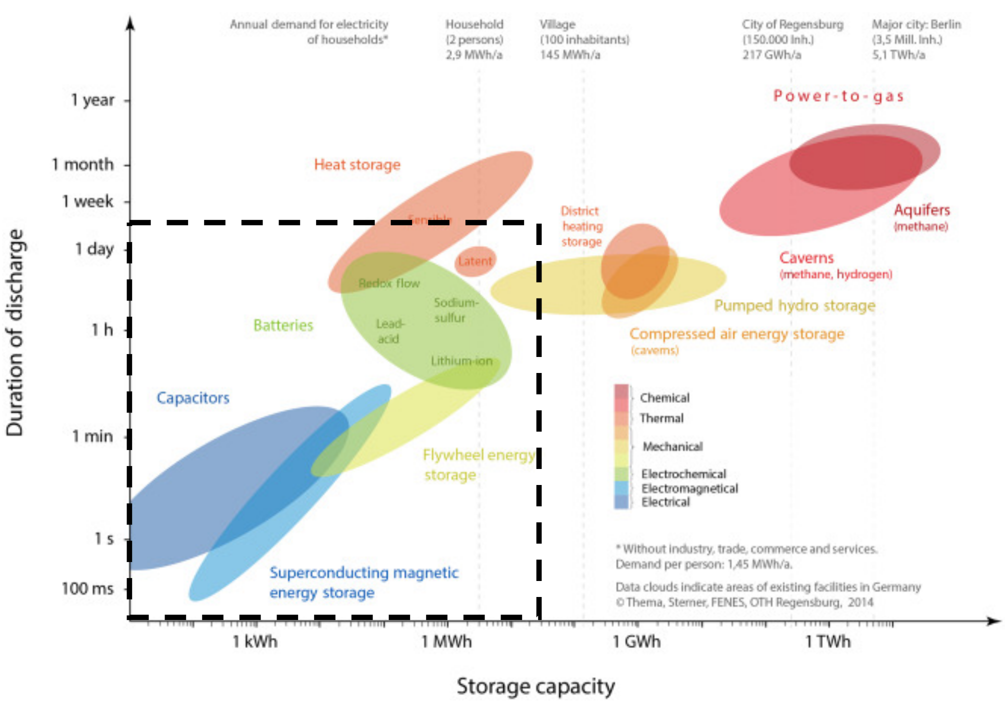

Figure 1. Ragone chart of different storage technologies (Droege).

This Ragone chart compares the storage capacity and the discharging duration for various storage types. With this type of visual, it is clear to see that our focus for this project will be on the left portion of the graphic, which shows mechanical, thermal, electrical, and electromagnetic energy storage.

For each of the four main energy storage categories mentioned above, we conducted more in-depth research to determine their advantages, disadvantages and applications. Applicable patents, shown on the next page in Table 1, and existing products are also mentioned below in the upcoming sections.

Table 1. Relevant energy storage patents.

Patent #	Title	Description
US6995529B2	Flywheel energy storage	An in-depth design of a flywheel with woven composite rings, allowing for high rotating speeds, reliability, and low energy loss
CN201733169U	Magnetic Flywheel	A flywheel with magnetic suspension for very low energy loss.
US20130271091A1	Ultra-capacitor-based energy storage in a battery form factor	Supercapacitor with capability to charge and discharge similar to that of a battery output
US10088243B2	Thermal Energy Battery with Enhanced Heat Exchange Capability and Modularity	Thermal battery intended to bridge power loss in rural areas of India, uses a heat exchanger
US9767948B2	Light-weight, efficient superconducting magnetic energy storage systems	New tape configuration so the toroidal magnetic field is oriented mainly parallel to the tape, reducing the cost of a SMES system

The patents in Table 1 speak to the full breadth of applications for energy storage, and each's distinct advantage. Thermal batteries are especially critical in places like rural India without developed infrastructure to carry out life-critical tasks. Supercapacitors can mimic the effect of a traditional battery system while simultaneously being built with less polluting components. Kinetic energy storage in the form of a flywheel addresses the critical feature of long-term energy storage with minimized losses – a key aspect of our scope.

2.4 Mechanical Storage Research

Mechanical energy can be broken into different types, but we will be focusing on kinetic and rotational energy. An optimal example for rotational energy storage is the flywheel. A flywheel is a system that contains a mass that is spun at high velocities to store rotational energy. With relatively low energy losses due to friction, flywheels can store energy for numerous hours. To output the energy, the flywheel spins a generator to convert the energy back into electricity.

Flywheels in general have many advantages over typical chemical batteries. They tend to be more efficient, as well as allowing for unlimited daily cycles, no degradation (30-year design life), fast response time, and recyclable design. Currently, there are a few existing products that use this technology; the Velkess Flywheel provides clean and safe energy storage at a much lower cost than traditional flywheels. Compared to lead acid batteries, the Velkess Flywheel provides storage 10% cheaper, 15% more efficient, and at least 10 years of service life (The Velkess Flywheel).

Another existing flywheel product is the Amber Kinetics M32. This flywheel is highly scalable and its main use cases are for microgrids, commercial applications, and solar storage (The Next Frontier in Energy Storage). In Table 2 are the specifications for these products on the next page.

Table 2. Existing flywheel products compared in terms of various specifications important to the overall function of the product.

Product Name	Power [kW]	Energy Storage Capacity [kWh]	Size [in]	Weight [lb]	Efficiency [%]	Price [$USD]
Velkess Flywheel	3	15	40” x 40” x 40”	3,750	80%	$6,000
Amber Kinetics M32	8	32	54” x 54” x 52”	10,500	86%	$30,000

Sources: (The Velkess Flywheel), (The Next Frontier in Energy Storage)

The market for these products is rapidly increasing. Flywheel installations are expected to grow from 6 gigawatts (GW) in 2017 to 40 GW in 2022 (The Next Frontier in Energy Storage). Improvements in cost and efficiency are currently being developed. A few relevant patents are listed in Table 1.

With the many benefits Kinetic storage provides, it still presents the challenges of noise and mounting frictional losses. With such a large spinning system, it would require magnetic bearings or a similar fixture to reduce contact resistance and the hum associated with spinning assemblies. Additionally, the system’s storage potential scales with size, so the more feasible applications will require significant areas set aside for operation.

2.5 Thermal Storage Research

Thermal storage systems employ similar technology to traditional Lithium-Ion battery cells, but their basic operating principles are different. Detailed in Guidotti and Masset’s paper, “Thermally Activated Battery Technology I: An Overview”, the authors discuss the structure of a thermal battery noting that the structure is cylindrical and encased in a metal shell laid over a fiber wrap. The operating principles are based around molten salt ionically conducting between the anode and cathode once the battery is activated. Since the battery needs an activation event to occur, this creates some characteristics specific to thermal batteries. They exhibit an extremely long shelf life with little to no degradation, so long as the activator pin is still engaged. Alternatively, the shelf life once engaged is substantially shorter and is unable to sustain continued recharges as well. Unlike a chemical battery, the thermal battery is intended primarily for single-use applications, harnessing the temporary but sizeable amount of energy generated from the molten salt. Argonne National Laboratories has researched and developed a rechargeable Thermal Battery cathode with varying degrees of success, though the discharge rates have improved (Guidotti).

Current applications of thermal batteries have primarily been for military ordinance, nautical torpedoes and space applications – all of which need a temporary energy source with an extremely high energy density. As their operation depends on the temperature of internal molten salt, many batteries must be insulated from damaging neighboring electronics (Kenner). These smaller batteries are primarily produced by an American firm, EaglePicher, which has been implemented in multiple NASA space missions for launch vehicles (“Thermal Batteries”). Newer commercial applications of the technology include CCT Energy, an Australian group constructing modular Thermal Batteries in shipping containers. They have implemented their system successfully with South Australian telecoms and real estate development groups in the United Kingdom. Pricing structure of thermal batteries is not widely covered, as many sales are to businesses and space programs, but CCT claims to beat Lithium-Ion battery storage pricing per kilowatt-hour by 20% to 30% with an upwards of five times more energy dense system (HR).

Patents specific to thermal batteries being implemented in developing regions have been filed, particularly with utilizing the excess heat energy developed by battery in conjunction with a heat exchanger. Marketed as a solution to rolling blackouts in regions of India, the device would be able to power milk chillers for more than six hours a day to eliminate spoilage of food for rural communities (Grama). In conjunction with a salt mixture, the system can alter its freezing point and chill the contents of the chiller.

Thermal batteries' flaws include the complex nature and steep investment for production. In a field application such as the developing regions this project targets, maintenance by technicians and availability of parts would prove to be a challenge. Additionally, these areas do not have the capital to invest in such a costly product to begin with, let alone keep it running.

2.6 Supercapacitor Storage Research

A supercapacitor has been described to be in between an electrolytic capacitor and a rechargeable battery, (Arrow). This statement generally speaks to the capacity of storage for the different electrical systems, as the physical make up is quite different. On a power storage scale, supercapacitors are essentially very powerful electrolytic capacitors. The total power can vary, but the difference is on the scale of thousands of times larger. Supercapacitors are very good at loading and unloading power at high current and short duration, which makes them very well suited to provide small bursts of energy, such as sending signals in varying applications. Our application, however, will need to provide power at longer durations, over many hours.

Batteries have electrochemical reactions that are able to produce electricity, whereas supercapacitors are non-electrochemical. Interestingly enough, the only reason supercapacitors include an electrolyte is to boost the capacitance, a commonly misunderstood fact. The discharge curve is very noteworthy between these two systems. Supercapacitors are only able to discharge a portion of their power before the output voltage drops below the limit, usually in the range of 45% of their total power. Historically, batteries are most widely used for applications where consistent power is needed because they can deliver 90-95% of their stored energy before reaching the voltage limit, (Battery University). On the other end, going over the maximum voltage when charging is also problematic, as it can short the capacitor and lose power.

At the University of Texas A&M, they developed a potentially game-changing discovery: the plant-based supercapacitor. They explained this capacitor "cuts costs on the dollar and the environment," (Lavars). The design is not in production for market sale, but there is a possibility in creating a supercapacitor system that is just as environmentally friendly as any other option. Intel was also able to invent an 'ultra-capacitor,' their patented design. The success of this design is in its charge and discharge curve, which is supposedly able to emulate that of a chemical battery, (Borkar).

Supercapacitors have made some exciting breakthroughs in recent years. They have showed that it is possible to beat out the standard electrochemical battery in many categories; most remarkably in Whr/kg, where supercapacitors can have 10-50 times greater energy densities than batteries, (Battery University). And most importantly from a business perspective, monetarily they are at a more competitive cost than ever before.

Supercapacitors encounter the issue of scale, particularly in depth of charge. Though their discharge and charge rates can handle incredible inputs, a system suitable enough to replace a traditional battery pack would require far too many components. Being supercapacitors, these are expensive to procure and could possibly be outpaced by changing technology in 10 years' time.

2.7 Magnetic Storage Research

Superconducting magnetic energy storage, also known as SMES, utilizes magnets as a way to store and quickly release energy. Within a SMES systems, DC current flows through cryogenically cooled superconducting coil and creates a magnetic field that stores energy (Letcher). Superconducting materials, while expensive, have an amazingly useful property that lends itself to energy storage. When the material is cryogenically cooled below its critical temperature, which is very close to absolute zero, electric current can pass through the wire with almost no resistance (Breeze). No resistance means no resistive energy losses as the current circulates through the system, making SMES systems extremely efficient. For reference, a diagram of a typical SMES system configuration is shown below in Figure 2 (Breeze).

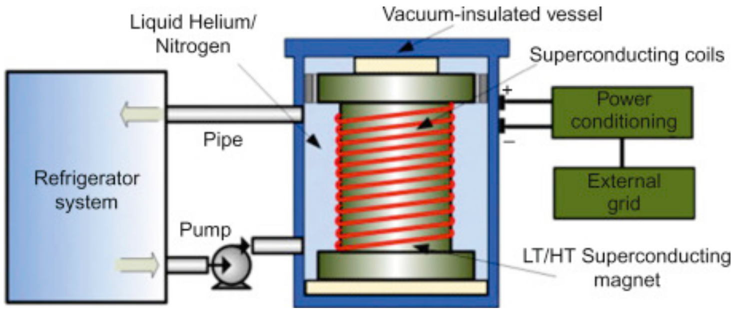

Figure 2. Diagram of a typical SMES system for a small commercial setting (Breeze).

As seen above, the superconducting coils are housed in a storage ring built into a container for easy transport and accessibility. Grid power drives the cooling system to ensure the storage ring is below its critical temperature.

Superconductors can be split into two categories – low-temperature and high-temperature. Low-temperature superconductors are on the more expensive side and have much lower critical temperature, requiring a cooling system with either liquid helium or liquid hydrogen (Breeze). High-temperature superconductors only require liquid nitrogen to cool them and are cheaper; however, their material properties actually make it so more material is required to create a system with the same storage capability as a system with low-temperature superconductor (Breeze).

SMES systems are commonly used as a quick remedy to grid interruption and sudden losses in power supply (Bindra). There are no moving parts within the system, so it has a fairly long lifetime. However, forces inside the ring caused by contraction while cooling and magnetic forces could cause fatigue fractures within the coils (Breeze).

For applications in developing regions, they need proven technology – a requirement of which magnetic storage is not. The field is still in its infancy and relies far too much on multi-layered systems, which introduce more failure points. The exorbitant cost and high maintenance schedule would prove difficult for the average consumer to keep up.

2.8 Storage System Comparison

We identified four key main areas of research that could be pursued further, demonstrating enough promise from our initial data. These were kinetic storage, thermal batteries, magnetic storage, and supercapacitors. The flywheel stores the energy as rotational kinetic energy, the thermal battery utilizes a molten salt mixture for energy storage, magnetic storage uses a superconducting magnet that is cooled by a cryogenic system, and the supercapacitor uses a porous membrane and electrolyte to store energy.

The strengths and weaknesses for each storage system type considered during our preliminary research is included in Table 3. Of the options eliminated, all were too complex for the project’s application.

Table 3. Summary of strengths and weaknesses for each energy storage type.

Energy Storage Type	Strengths	Weaknesses
Mechanical	Efficient, cheap, long lasting	Weight, noise, size, higher loss potential
Thermal	Long lasting	Expensive, many components, less suitable for small scale
Supercapacitor	High discharge rate, reliable	Expensive, requires more components for steady output
Magnetic	Efficient, scalable	Expensive, complex, developing research area

The kinetic flywheel storage system was the best of the four options, proving to be cost effective, with low maintenance and sufficient energy density and the choice we decided to move forward with. Ultimately, the thermal battery showed promise with incredibly high energy density, but was not feasible to construct and is historically used in one-time energy uses like missiles. Likewise, magnetic storage has very few frictional losses, but manufacturing a cryogenic chamber that requires little to no maintenance would be an incredibly difficult task. Although the supercapacitor had the most impressive specifications, the option was ruled out due to the exorbitantly high cost to procure the correct volume.

3 Objectives

Setting clear objectives and expectations for a project is extremely important. In this section, we will explain our problem statement, how our design will interact with its environment, and our Quality Function Deployment process.

3.1 Problem Statement

Households in developing areas need off-grid power storage that is both cost efficient and scalable. As renewable energy sources are becoming more economically viable for small scale power production, there opens up a need for a sustainable option to store the excess energy. The current products on the market largely rely on chemical batteries to store excess energy. However, these batteries have a large cost on the environment to both produce and recycle. It is not good enough to have clean energy without clean storage; the system has to be environmentally favorable throughout.

3.2 Boundary Diagram

The boundary diagram, as seen in Figure 3, aims to give an accurate depiction of the solution on a general scale and how it interacts with its environment. The product we are designing will be connected to some sort of power source, such as a small turbine or solar panels. When the power sources are overproducing what the house demands, excess power will funnel into the storage system. Then, as most renewables are intermittent, when the power addition drops the house can start to feed from the energy capture system. To an outsider's eye, it only needs to look like a "black box" that stores the energy, they do not need to understand the inner workings. Ideally it would be very inconspicuous, sitting most likely on the outside of a house or in a basement. The maximum size has been outlined in Appendix A and states a maximum volume of 1 cubic meter. The volume will hopefully be scalable to the size of the house connected, but with this as the maximum size.

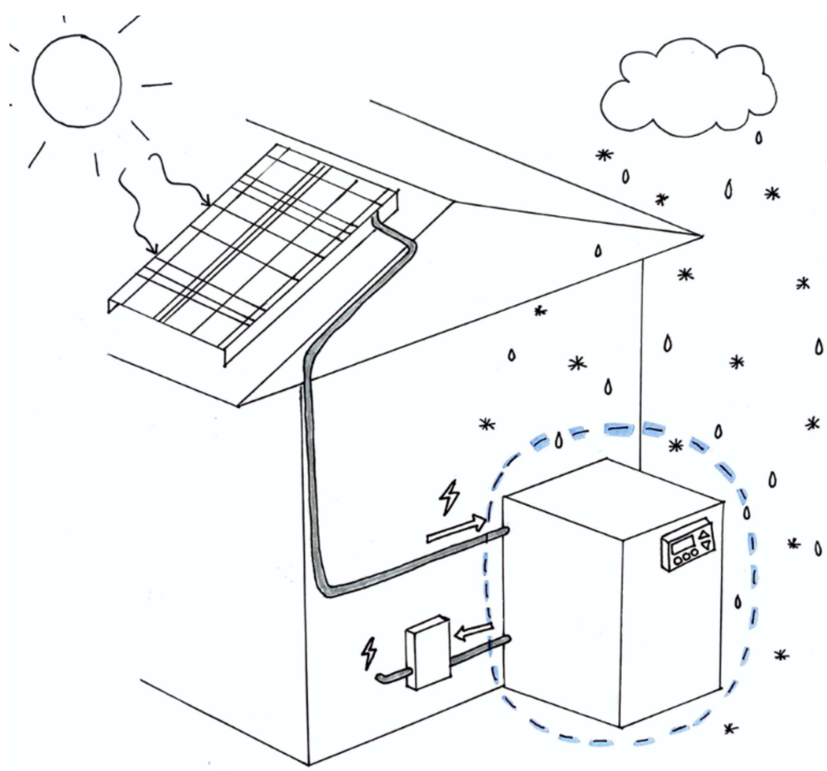

Figure 3. *Boundary diagram sketch.*

3.3 Customer Needs and Wants

An important part of understanding the engineering problem and our project as a whole is to effectively identify the customers' needs and wants. These needs explain the desired features of our product, help us to compare our design to other products, and ultimately give us requirements for a good and successful design. Table 4 below lists all the customer needs and wants we identified. A description and explanation of importance is also included for each need.

Table 4. Description of customer needs and wants.

Customer Need/Want	Description
Stores sufficient energy	The normal amount of power that the storage system should be able to supply for a given duration. This will determine which utilities in a home can be powered.
Compact form factor	The expected size and weight of the storage system. It needs to be small enough to fit outside of a house and should be light enough for feasible installation.
Quiet	The energy storage system needs to be quiet enough for residential use.
Cost efficient	The target price for the system should be reasonably low so that customers can afford it
Safe operation	The system needs to be safe enough for homeowners.
Low maintenance	The system should be reliable, especially for those in developing areas that will depend on it.
Sustainably sourced materials (Non-toxic)	The aim of this product is to store energy sustainably. The materials used should be less toxic than chemical batteries.
Low energy loss	The efficiency of the storage system. It should be able to return enough power to still be profitable.
Conveniently controlled by user	To be practical, the average person should be able to control the system with ease.
High energy density to weight ratio	The system design should be able to store a reasonable amount of energy when given a desired size.
Manufacturability	The system needs to be easily manufacturable for lower cost and faster production.

3.4 Quality Function Deployment (QFD) House of Quality

Quality Function Deployment is a way to transform customer needs and wants into tangible engineering specifications that can reliably tested. It helps us as engineers to properly understand intended problem and what the customer ultimately wants. A House of Quality is the end result of the QFD method and is a diagram that consolidates the relationships between customer requirements, engineering specifications, and current competitors. Our House of Quality can be found in Appendix A at the end of this report.

The first portion of the QFD House of Quality is identifying the customers, but customers are not only the end users of the product. For this reason, we included three different customers – off-grid customers, manufacturers, and residential homeowners. Since the storage system we will design needs to be stackable, and therefore able to accommodate small and larger sized power demands, we included off-grid and residential homeowners.

With all customers identified, the customer needs and wants can then be listed on the left most portion of the House of Quality. A total of eleven needs were determined and weighted, of which the most important being safe operation, sustainably source and non-toxic materials, and sufficient energy storage capacity. The power requirements and targets are based on the needs of a homeowner living in a rural area that is not connected to the grid and dwelling in a developing area of the world. Based on our research of domestic homes, we found that a reasonable maximum power output would be 1kW. This would be enough to power one important appliance such as a fridge or small heater. On average we would expect an average of 0.5 kW power usage from a house in a developing area. This value was estimated based on the data from domestic homes and scaled for expected power pull of off-grid homes or developing areas. With these numbers in mind, we can calculate that the overall storing capacity should be 3.5 kWh to provide seven hours of power output at full charge. The charge time should be around eight hours given that our charging system will be from solar panels, and that is usually the amount of viable solar power production during the day. The volume, weight, and cost targets are goals for making our design a practical domestic installation.

After a thorough determination of customer wants and needs, we move on to benchmarking the competition. The most common type of residential sustainable energy storage systems on the market are those that rely on chemical batteries; even though our project is strictly focused on non-chemical battery storage systems, we thought it was important to include the Enphase Ensemble as one of our competitors. The three remaining products we chose were the Velkess Flywheel, CCT Thermal Battery, and Capacitor Bank. Each competitor was then assessed on a scale from 1 to 5 how well they satisfied the customer requirements.

For the benchmarks our system must achieve, we identified the most critical features our storage system must meet in order to surpass the current market competition and organized them into measurable goals, as shown below in Table 5. To the left, 'Specification Description' identifies the feature to be assessed followed by the measurable goal in the following column titled 'Requirements'. The 'Tolerance' column categorizes the requirement as a limit to surpass or remain below and the 'Risk' column specifies the severity of the feature by denoting (H)igh, (M)edium, or (L)ow. Finally, the compliance column denotes the type of compliance necessary for each specification with (A)nalysis, (T)esting, (S)imilar, and (I)nspection.

Table 5. Engineering specifications, target values with allowable tolerances, risk assessment, and methods for determining compliance.

Spec. #	Specification Description	Requirement or Target (units)	Tolerance	Risk	Compliance
1	Maximum power output	1 kW	Min	H	T, A
2	Sustained power output	0.5 kW	Min	H	T, A
3	Noise measurement	30 dB	Max	M	T
4	Market cost	$5,000	Max	L	A
5	Volume	1 m^3	Max	M	I
6	Weight	750 lbs	Max	L	I
7	Manufacturing cost	$2,500	Max	M	A
8	Power loss	5% per 8 hrs	Max	H	T, A
9	Storing capacity	3.5 kWh	Min	H	T, A
10	Charge time	8 hrs	Max	M	T, A, S
11	Group appearance rating	70%	Min	L	T, I

Each specification needs a way to be tested in order to ensure our design has met the necessary requirements. Below is a more thorough description of how we will measure each specification mentioned previously.

1. Maximum power output will be measured by connecting a maximum load, which was determined from a max load case of having a refrigerator, dryer, and A/C unit running simultaneously.
2. Sustained power output will be measured by connecting a load with a known voltage and current draw, then timing how long power can be supplied to it. This was determined in part due to the maximum power output metric and scaled to a reasonable estimate.
3. Noise measurement will be measured by running at maximum power output and using the Decibel Reader application to obtain the dB reading. This was determined to limit noise to the noise intensity of a whisper as to not interfere with daily life.
4. Market cost will be measured by calculating price using a standard profit margin. The $5,000 figure was chosen in order to be competitive with the Tesla Powerwall, currently priced at $5,500 for a 3kWh system.
5. Volume will be measured by physically measuring the lengths of all three sides of the system and multiplying them together. The 1 m^3 metric was decided to be on par with a conventional Swamp Cooler that one may have on the side of their house.
6. Weight will be measured by using a scale. Similar to the size, this was to be on par with the weight of a conventional Swamp Cooler.
7. Manufacturing cost will be measured by totaling all costs associated with the production. The $2,500 figure is set in part due to our initial $2,500 budget for this senior project.
8. Power loss will be measured by comparing sustained power output after a given time. Power losses were set to be a conservative loss rate and in line with industry targets.
9. Storing capacity will be measured by testing sustained power output and multiplying by time. The 3.5kWh benchmark was selected from preliminary research and the average energy usage of a tiny house.
10. Charge time will be measured by measuring input current over time. The 8-hour figure was determined based on peak energy usage and duration of non-production energy usage.
11. Group appearance rating with be measured by surveying the target market once a prototype has been created.

A critical feature of our project hinges on how our customer needs interact with the engineering specifications set forth in the QFD. Regarding form factor, the system's size was highly determined by the energy density and volume of the system. Production from sustainable materials, manufacturability, and unit cost are all factors that feed into the manufacturing and market cost of the storage system in the end. Factors like low maintenance or safe operation were moderately linked to specifications such as power output and weight, which can affect costs in the future. Lastly, features such as quiet operation are primarily linked to noise measurement, but is additionally linked to volume, maintenance and charging metrics.

4 Concept Design

For the next sections of the report, our team made the decision to focus our project onto flywheel energy specifically. Up to this point, the majority of our time and effort was allocated to researching many different methods of energy storage. Keeping the next part of the design process as generic and large scale as before would render much of the work useless.

Flywheels became the frontrunner for our design direction because of the feasibility and effectiveness of these system types. Supercapacitors have the potential to be a great storage technique with their high charge and discharge rates but come at a very high cost. This option was ruled out mainly because it would not be practical. The project would be unfeasible if the design we aimed to implement in developing countries and small off grid homes was extremely costly. Even though thermal storage was a very close second, those types of systems have many complicated subsystems in order to convert the stored heat energy into electrical energy. A subsystem is necessary to convert the energy that both increases costs and complexity. Finally, magnetic storage was not chosen because it is an extremely new technology that needs more development before implementation in the real world. Even though flywheels come with their own drawbacks, they have high energy densities, the potential to be constructed of sustainable materials, and, if frictional elements are mitigated, great potential for energy storage. A detailed Pugh Matrix of our decision process can be found below in Table 6.

Table 6. Simple Pugh Matrix comparing the four major energy storage proposals

Criterion	Powerwall	Kinetic	Thermal	Magnetic	Supercapacitor
Cost	**0**	**+**	**-**	**-**	**-**
Reliability	**0**	**0**	**-**	**-**	**0**
Efficient	**0**	**-**	**+**	**+**	**0**
Manufacturability	**0**	**+**	**0**	**-**	**0**
Total	**0**	**+1**	**-1**	**-2**	**-1**

The following sections outline the conceptual design process our team followed. We used ideation methods to come up with out of the box ideas, which were weighted and ranked to help find the best path for our project.

4.1 Concept Development and Ideation

Our first step in ideation was creating a functional decomposition. This process allowed us to break down the desired deliverable into its main functions and their sub-functions. These functions were then placed in the function tree, shown in Figure 4. Starting from the highest level, we determined that the main function of our project would be to temporarily store energy for later use. Branching from this function, we decided on subfunctions that would be expected from our customers and sponsor. Finally, we broke these sub-functions into lower-level operations that would work together to provide a working product.

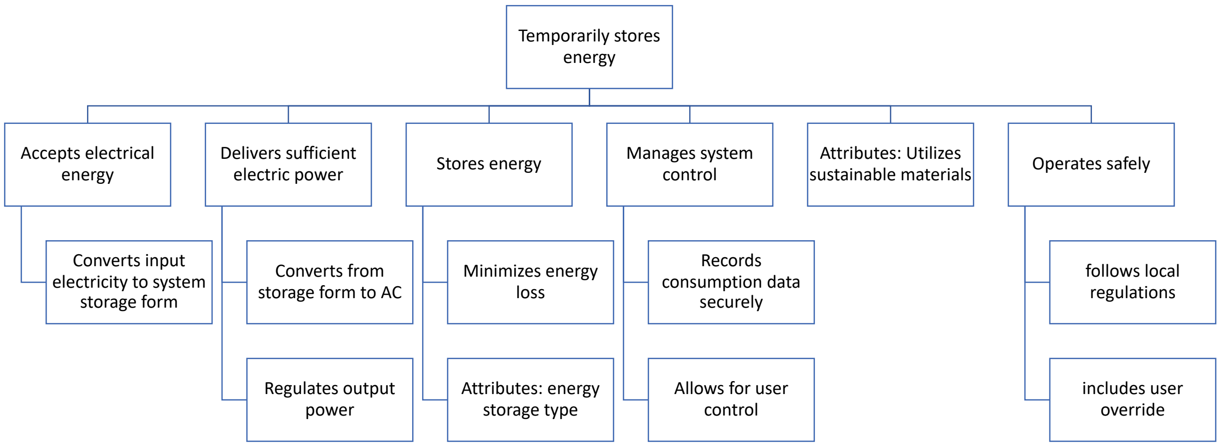

Figure 4. Function Tree Diagram.

After creating our Function Tree Diagram, our next step was to come up with as many ideas as possible for each function. For this ideation step, we used brainstorming on Google Jamboard. Images of this process are included in Appendix B. Group members worked together to write down any ideas they could come up with for each function. After documenting all of our ideas, we eliminated the undesirable ones and kept the others to be added into our decision matrices in the following sections.

4.2 Pugh, Morphological, and Decision Matrices

The chosen direction for the course of the project was decided with the help of the following design matrices. Pugh Matrices compare function level designs against each other to bring a better understanding and easier ideation at a low level. Morphological Matrices help to combine the ideation results into full systems, and the Weighted Decision Matrix assigns point values to these systems to direct our team in the correct path.

4.2.1 Pugh Matrices

Pugh Matrices are simple charts that compare various ideas for a specific function based off a datum. The most average, middle-ground idea is chosen as the datum and is used as a baseline to rate the other ideas. This allows our team to see very easily which idea is best based off all the needs we have. For the Pugh Matrices, the datum receives a score of 0; the other ideas for each specific function are rated with a +, -, or S to indicate if it's assumed to be better than, worse than, or the same. Each '+' the idea is awarded adds one point to its final score, and the opposite for a '-,' subtracting a point. 'S' is an input to represent that for that function the idea is similar to the datum, not hurting or helping the total for that idea.

Our team developed five Pugh Matrices, and they are all outlined in Appendix C. The five were derived from our Function Tree, and due to the similarity of the Accepts and Delivers Electrical Power, they were combined into a single category for the Pugh Matrices. This step in the design process helped to focus our outlook onto the best ideas for each applicable function to continue.

4.2.2 Morphological Matrix

The intent for Morphological Matrices is to combine ideas of different subsystems into a single collective idea, thereby incorporating the team's best ideas into something new. Diving into each specific function and ideating within those allows the process to become less overwhelming, by breaking down a larger problem into smaller pieces. The Morphological Matrix we created for our flywheel design direction is displayed in Figure 5. For each of the leading ideas for each section, our team drew up sketches to further explain the idea and supplemented those drawings with descriptions. These ideas and explanations can be found in Appendix D.

The more we started coming up with combinations and linking subsystems together, the more our team realized that our functions were much more independent than anticipated. Nonetheless, this matrix helped visualize the connection between components, and five different ideas were created based on this phase in the design process. These ideas are outlined and discussed in the following section, Decision Matrices.

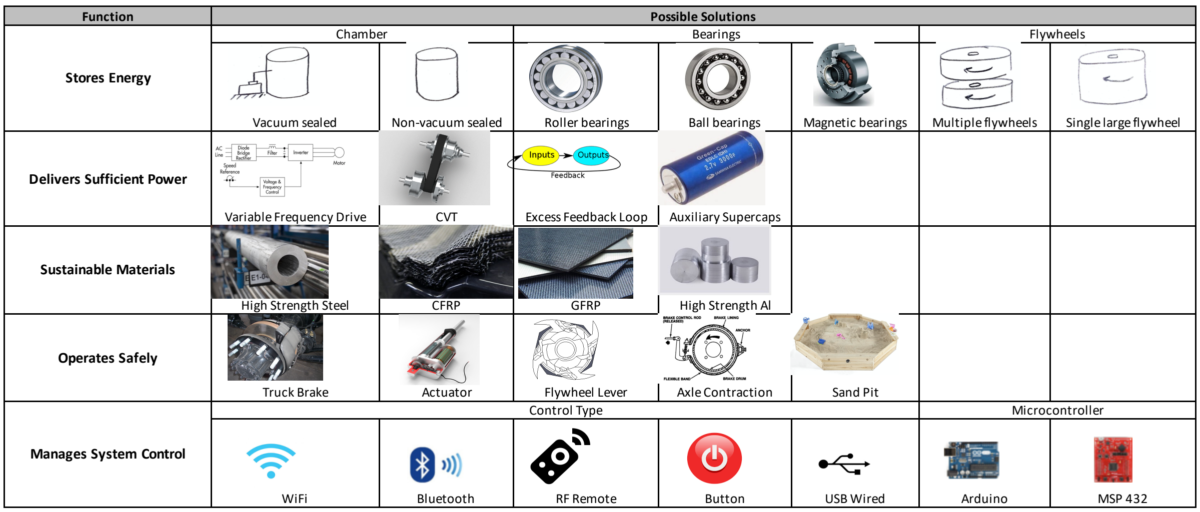

Figure 5. Morphological Matrix.

4.2.3 Decision Matrices

After creating our Pugh Matrices and Morphological Matrices, we were able to combine our top ideas for each function and arrive at multiple top system-level design ideas. Each of these ideas were evaluated in a Weighted Decision Matrix to determine the best option. The ideas, corresponding description, and sketches are shown after Table 7.

Table 7. Weighted Decision Matrix.

Specification	Weight	Idea #1	Idea #2	Idea #3	Idea #4	Idea #5
Stores sufficient energy	5	4	5	4	5	3
Compact form factor	2	3	3	2	1	5
Quiet	3	4	5	3	2	3
Cost Efficient	4	3	2	4	2	5
Safe Operation	5	5	4	5	5	5
Low Maintenance	3	3	2	3	3	5
Sustainably Sourced Materials (Non-Toxic)	4	5	5	5	5	5
Low energy loss	5	3	5	3	5	1
Conveniently controlled by user	3	5	4	5	5	2
High energy density to weight ratio	3	3	3	3	3	3
Manufacturability	3	3	2	3	2	4
Totals		152	152	151	150	146

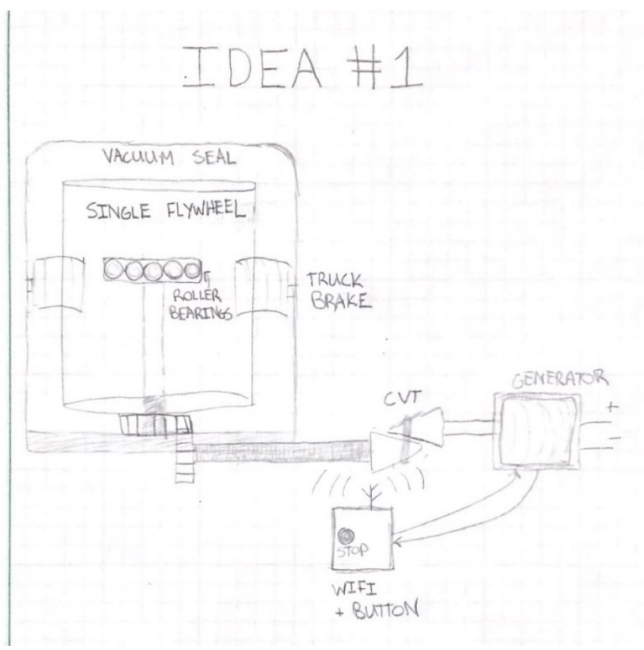

Figure 6. Idea 1 sketch.

Figure 6 shows our first idea, which is a vacuum sealed flywheel with roller bearings to reduce friction and store energy for a longer amount of time. A continuously variable transmission system is included to insure the correct amount of power is outputted at a given time. To safely stop the flywheel, a truck brake is used. This system is controlled by an Arduino microprocessor with a WiFi chip to allow for transfer of data and requests. As a safety precaution, a stop button will be included as well. Overall, this design will be decently efficient, store power for a long time, and be easier to manufacture.

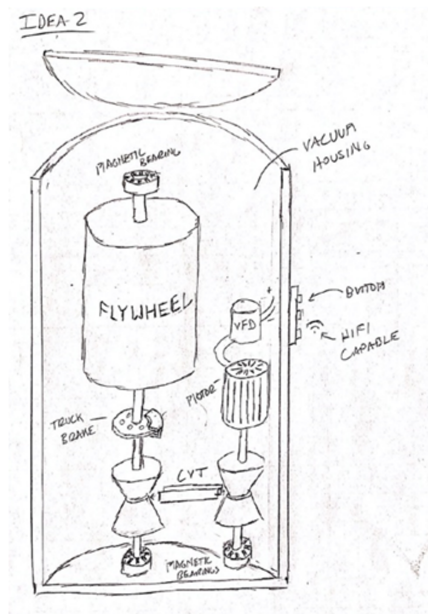

Figure 7. Idea 2 sketch.

The second system, shown in Figure 7, that was created from our ideation session is one that incorporates, to the best of our knowledge, all of the top of the line components. This was aimed to achieve the lowest frictional system possible. Magnetic bearings are used, and a vacuum sealed chamber contains the whole system. Continuously variable transmission and a variable frequency drive were chose to output consistent power. The other design decisions for this model were derived using the same logic as idea 1.

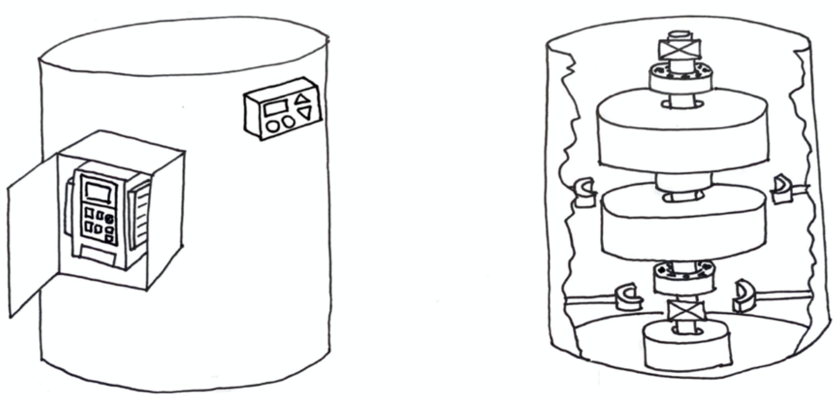

Figure 8. Idea 3 sketch.

Figure 8 illustrates the third idea, aiming to combine some of the high efficiency, high-cost elements with lower cost elements. The multi-flywheel system for this sketch, we depicted only 2 will be contained within a non-vacuum sealed chamber. The variable frequency driver used to control and deliver desired output power is shown located outside the containment chamber in a separate openable box, but it could also be housed inside the chamber. The multiple flywheels would be supported mainly by magnetic bearings but will also require backup ball bearings. Linear actuators will act as the emergency stop mechanism; when activated, they will clamp around axle and slow down the system. This idea proved to be too expensive for our budget and customer needs.

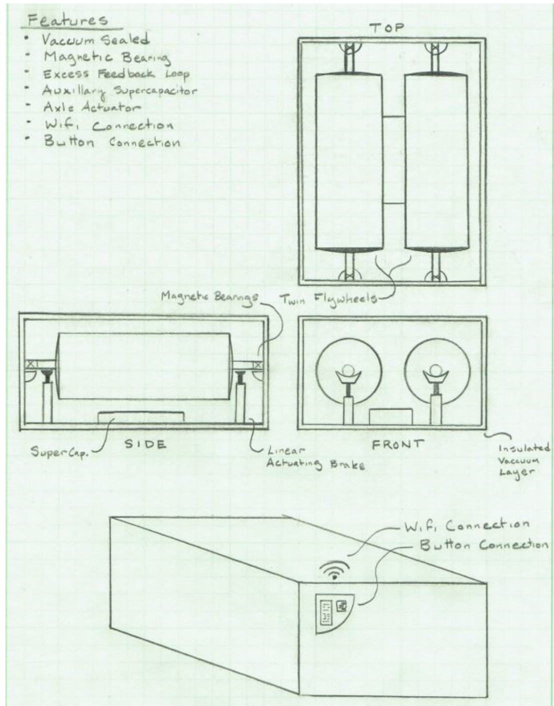

Figure 9. Idea 4 sketch.

Our fourth idea aims to utilize the more high-tech options available to build a flywheel, as shown in Figure 9. The design incorporates a vacuum-sealed chamber to reduce losses from friction as well as magnetic bearings to reduce resistance as the rotors spin. Using a twin flywheel system, the rotors can spin up and down independently to allow for load balancing and energy distribution to multiple loads. The Excess Feedback Loop allows for the control system to respond to real-time updates and conditions of the flywheel so that it may proactively charge and manage the system. This loop works in tandem with the auxiliary supercapacitor to discharge energy to be used for loading scenarios.

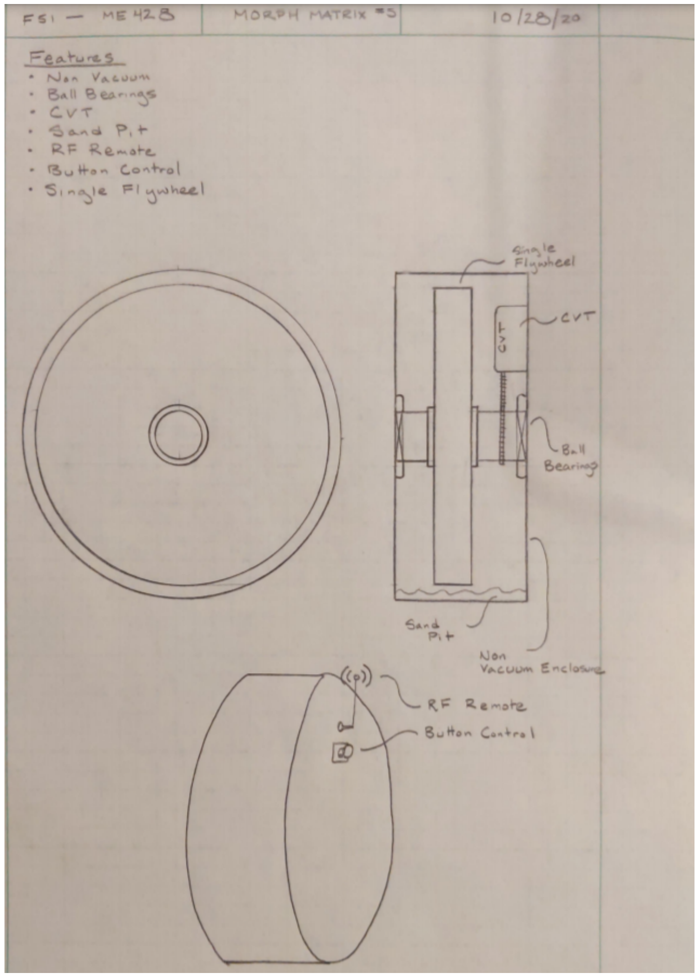

Figure 10. Idea 5 sketch.

The concept design in Figure 10 is more on the basic side and uses a single flywheel system housed in a non-vacuum sealed chamber. The flywheel would be supported and aligned by a series of ball bearings. Similar to some of the other designs, it utilizes a CVT. A large sandpit beneath the flywheel would act as the emergency stop mechanism; when activated, ball bearings would disengage and the entire system would fall into the sand, or other friction material to be brought to a stop. User control would be from an RF remote and a button on the unit. An RF remote would not require the user to have access to another device like a cell phone or a laptop.

4.2.4 Concept Design Decision

From our Weighted Decision Matrix, Ideas 1 and 2 were tied. Based on the feasibility, complexity, and cost of each design, Idea 1 seems to be the right choice. Idea 2 utilizes magnetic bearings, which have been difficult to accurately source or find an estimated base cost for. Therefore, Idea 1, which uses easier to source roller bearings, would be more feasible with our current knowledge and budget. However, to make up for the loss of efficiency due to the switch from magnetic to roller bearings, Idea 1 still incorporates the use of a vacuum chamber to reduce thermal losses due to friction.

4.3 Final Concept Design

As mentioned previously, the most important decision we made regarding our final concept design was pursuing kinetic energy storage with a flywheel. With the various types of energy storage previously researched, it was important to narrow our focus to one. After interpreting our results from both the Pugh

Matrices and the Weighted Decision Matrix, it became apparent that our functions were independent from one another, making the decisions from the Weighted Decision Matrix almost entirely obsolete. Due to this functional independency, components can be mixed and matched in any way, creating a large amount of possible design directions. We are now heavily relying on our Pugh Matrices to help indicate which solutions within each function are superior and would create the most efficient design, while still meeting all our specifications and budget limitations.

We have determined a general final design direction that encapsulates all the necessary sub-system concepts. As time goes on, it is likely our direction might shift slightly as more research is collected and a better understanding of each idea's feasibility is developed. A labeled isometric view of our CAD model can be seen in Figure 11.

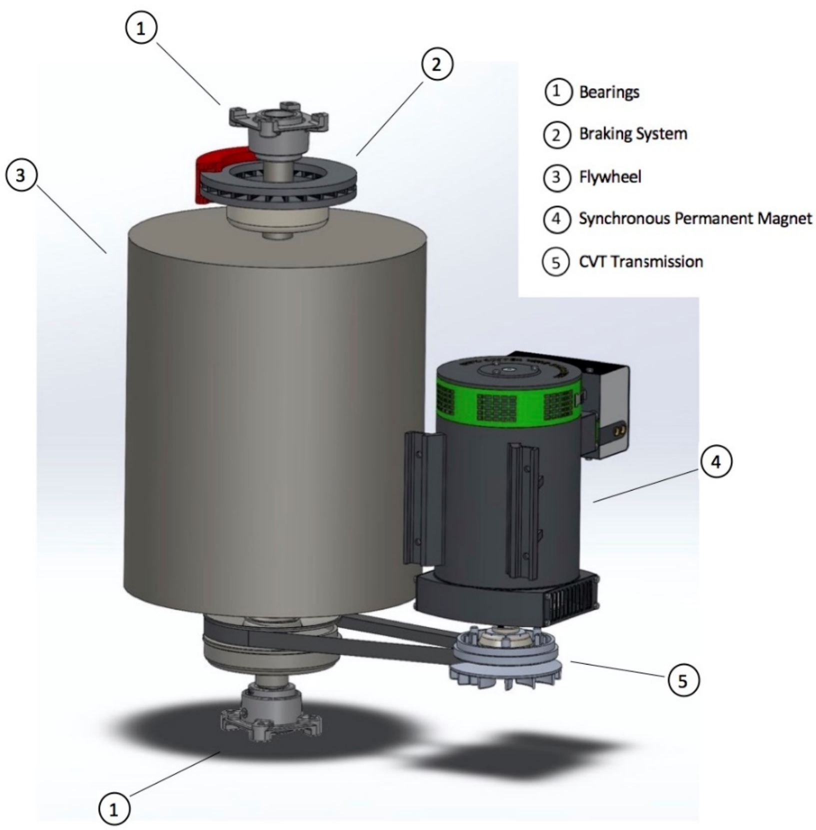

Figure 11. Flywheel energy storage system conceptual design.

The function relating to storing energy can be broken into three subfunctions: supporting elements, rotary configuration, and containment. Our design features roller bearings, a single flywheel oriented vertically, and a vacuum-sealed chamber. Despite magnetic bearings enabling better efficiency for the system, we have decided to go with roller bearings because magnetic bearings are extremely expensive, complicated, and hard to source. Since our project has more of an exploratory research focus, our goal is to design and, optimistically speaking, build a flywheel energy storage system that could rival the fully established chemical battery storage system. In a perfect world with no budget, this would likely contain magnetic bearings. However, our final product will most likely be a scaled-down proof of concept that switches to more easily manufactured and sourced components.

To deliver sufficient power to the house, a CVT system will be used to alter gear ratios to speed up or slow down the generator's rotation. Due to overall cost and manufacturability, we are currently deciding to use high strength steel for the single flywheel. The user will manage system controls through both a button and an Arduino microprocessor with a Wi-Fi chip. As a safety precaution, a truck brake, which is highly effective and can be easily purchased, will act as an emergency shut-off.

As this design has many integrated systems and electronic components, building a small-scale concept prototype out of common materials, such as paper or cardboard, would not be of much help when trying to understand the functionality of the system. Instead, we decided to purchase a small motor and gyroscopes to help understand how the two main components of our system will interact and what alternate layouts could look like. Below in Figure 12 the components described are pictured, as well as a solar panel illustrating the overall system.

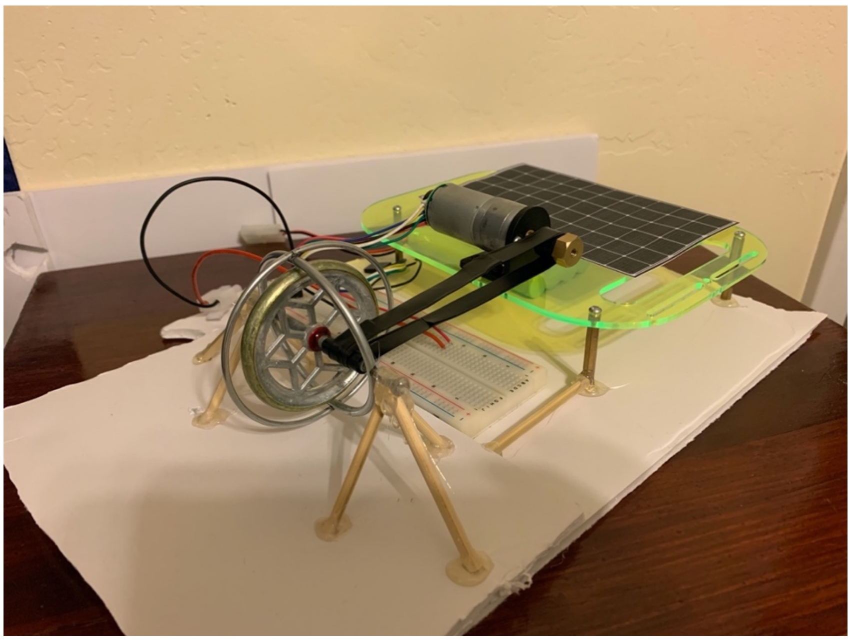

Figure 12. Concept prototype for flywheel system.

In order to demonstrate our design will satisfy the project specifications, preliminary analysis was done to check the amount of energy a specifically sized flywheel could store. We assumed all mass was concentrated along the edges of the flywheel with outer radius of 0.4 meters, inner radius of 0.38 meters, and a drum length of 0.5 meters. These preliminary dimensions still allow the system to be fully contained within a 1 cubic meter container. When run at a rotational speed of 10,000 rpm, the flywheel could ideally store 3.9 kWh, which is higher than our requirement of 3.5 kWh. A more thorough explanation of variables and full hand calculations can be found in Appendix E.

However, after talking to Professor Majid Poshtan from the Electrical Engineering department here at Cal Poly, it was brought to our attention that the biggest design concern will not be storing energy, it will be maintaining the energy with respect to any frictional losses. As we move forward with the project, we will need to estimate frictional coefficients of bearings and drag occurring on the top and sides of the flywheel to truly see if the losses due to friction within the system make this design feasible.

4.4 Preliminary Design Risks
As expected, this project poses many expected challenges both in minimizing current safety risks and meeting our specified goals. Due to the large rotating mass experiencing frequency acceleration and deceleration, many hazards on the Design Hazard Checklist, found in Appendix F, apply to our project.

The system will be running at a high speed, around 10,000 rpm, so one potential challenge is finding bearings that have high enough rated speeds and are sized to the shaft design we deem appropriate. As discussed earlier, storing energy for a sufficient amount of time will pose a challenge due to possible frictional losses. Another component of the design that will introduce difficulty is the feedback loop integrated into the system in order to control output power.

Among other safety risks is the chance for user error. Being a system that will be on display at the Senior Project Expo, it is of utmost importance to protect the general public from harm. A primary defense against this is to encase the system in a sheet metal skin, preventing a passerby from encountering the rotating mass and becoming entangled. Additionally, vertical members will be introduced in conjunction with the load-bearing corner lengths to effectively cage in the system.

The system, being one that stores energy, will introduce the possibility of electrical shock in the event of poor grounding. We intend on addressing this with our design.

5 Final Design

Since the final concept design resulting from PDR, our final selected design has significantly changed. Most notably, the motor is in line with the shaft, overall shaft dimensions have been drastically reduced, and the storage capacity has shrunk. These changes stem from a culmination of feasibility and safety limitations that will be addressed in the following sections.

After a thorough discussion with Cal Poly faculty regarding operating the flywheel at high speeds, our team made the decision to only test the system at low rotational speeds while still achieving educational outcomes from the tests. The following final design discussion serves to accurately describe the final state of our prototype.

5.1 Final Selected Design

Our final design is a scaled and simplified prototype, aimed to demonstrate the feasibility of flywheel energy storage. Due to budget and feasibility constraints, proving the concept on smaller scale allows us to scale our findings to meet the design specifications outlined earlier in the report.

From a top-down view, the verification prototype is able to accept power in the form of electrical energy and uses the BLDC (Brushless DC) motor to spin the flywheel to desired speeds. With a low friction environment, the flywheel is able to hold this power in rotation for an acceptable amount of time. When the consumer desires power output, the control system can connect the load and the current will reverse directions. This causes the motor will act as a generator, converting that power back from rotational to electrical for use.

The flywheel energy system, as shown below in Figure 13, can be separated into five key subsystem – flywheel and shaft, bearings, braking, chassis, and motor.

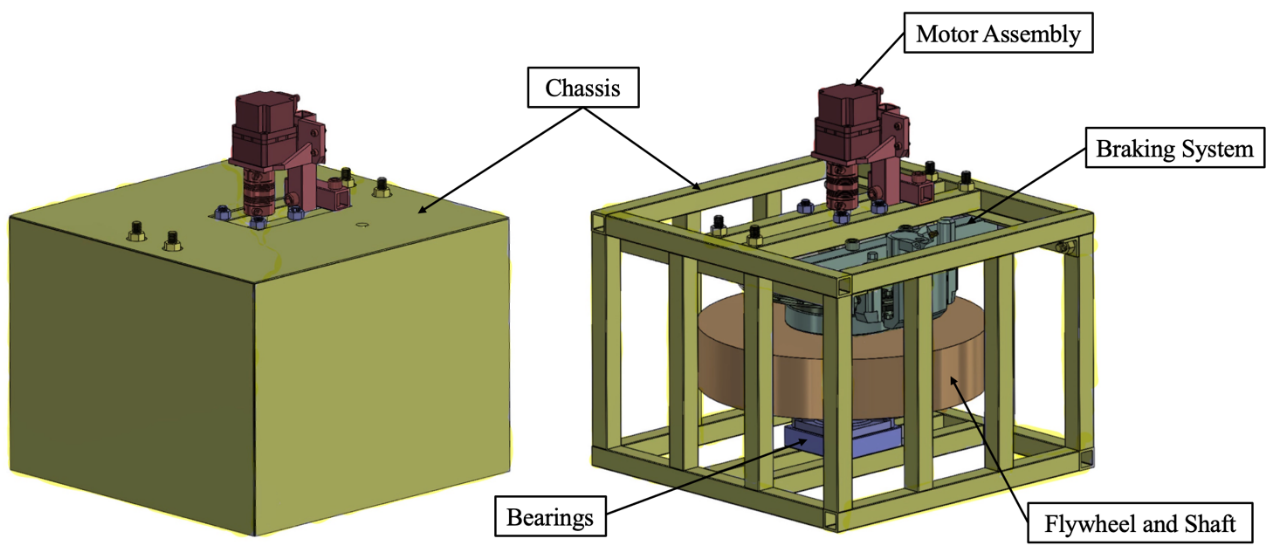

Figure 13. Isometric views of flywheel energy storage system with steel siding (left) and without (right).

The following subsections will describe each part of the final design in more detail, including a discussion of components and important considerations that influenced our finalized design decisions.

5.1.1 Shaft and Flywheel Subassembly

The shaft and flywheel subassembly contains the shaft, flywheel, and machine key, shown in Figure 14 below. When considering our flywheel design, it was important for our flywheel to have the majority of its mass concentrated as far away from the axis of rotation as possible. For a solid cylindrical disk, the mass moment of inertia is calculated by multiplying the total mass by the square of the cylinder's radius. The system's energy storage capability is directly related to the mass moment of inertia, so any increase in the radius will greatly increase the possible energy storage. To ensure stability, the flywheel's ratio of diameter to height had to be either much less than or much greater than 1:1 (Liu). By avoiding ratios near 1:1, we avoid causing further vibrations at the ranges where the system operates. Due to sourcing parts and overall pricing, we decided to use a 3" tall and 14" diameter aluminum disk as our flywheel.

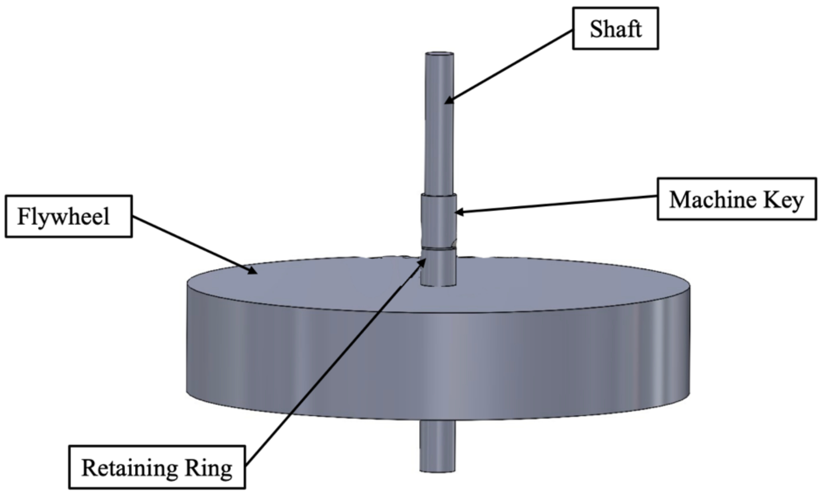

Figure 14. Isometric view of shaft and flywheel subassembly.

The mating of the flywheel and the shaft was critical to our design and includes a press fit, machine key, stepped seat, and retaining ring to fully constrain the flywheel. As seen in assembly Figure 14 above, there is a substantial gap between the flywheel and the retaining ring. The brake rotor and spacer, further explained in Section 5.1.3, will fill that space and in conjunction with the bolts, will securely locate the flywheel vertically on the shaft. These critical components are discussed at length in the analysis section of the report and detailed in the drawing package.

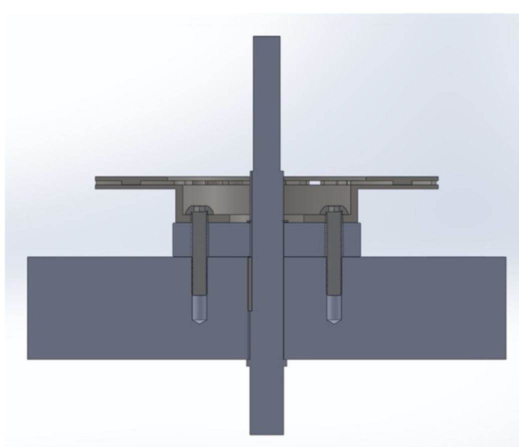

Figure 15. Cross-sectional view of flywheel subassembly with joining braking subassembly.

The cross-sectional view of the flywheel in Figure 15 depicts the interaction between the key components discussed. The brake rotor and brake spacer were included for ease of understanding of the inner workings of the all the rotating elements, along with the flywheel subassembly itself.

The axis of rotation was oriented vertically for multiple reasons. First, the bearings were most effective when the weight of the system would be supported by an efficient thrust bearings and disturbances would be supported by the radial bearings. Secondly, if the system is orientated horizontally, the weight of the mass along the shaft can introduce bending over time. If this imbalance persists, then operating at high RPM's can become a significant issue.

5.1.2 Bearing Subassembly
The bearing subassembly, detailed in Figure 16, consists of upper and lower bearings, as well as the thrust bearing and its custom housing. Ultimately, an ideal design would implement the use of a magnetic bearing system, which would reduce friction losses as well as lowering noise pollution. However, as mentioned previously, magnetic bearings are extremely expensive and difficult to source.

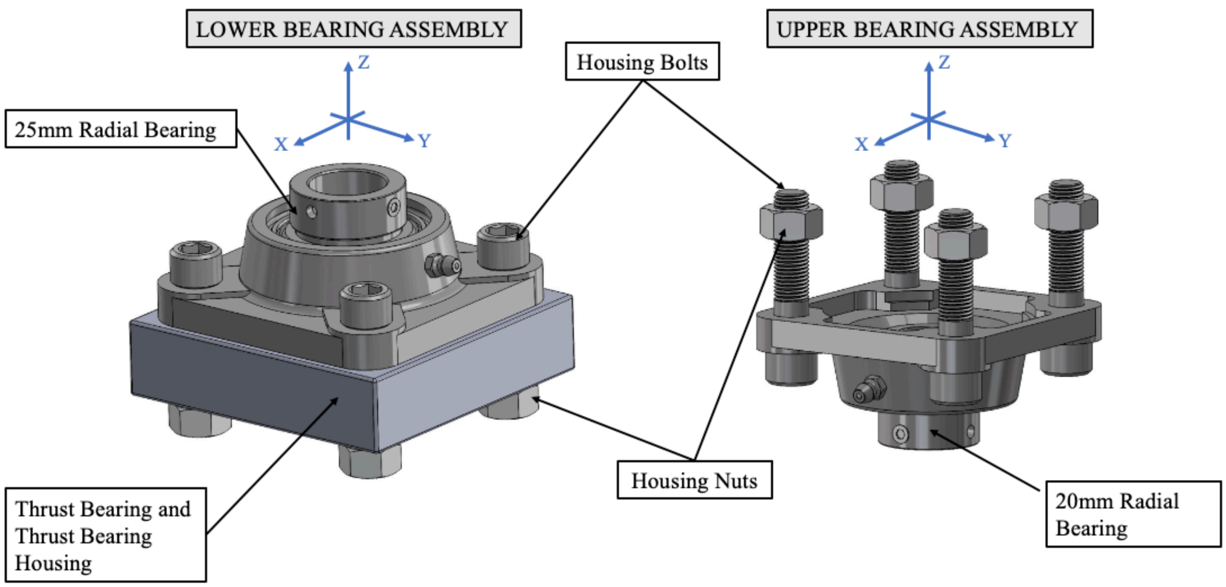

Figure 16. Lower and upper bearing assemblies.

As part of the proof-of-concept model, roller bearings work together to constrain the X and Y axis movement. We elected to only use a single roller needle thrust bearing on the bottom to constrain the Z-axis, as the probability of the system rising upwards is eliminated by the overwhelming mass of the flywheel piece.

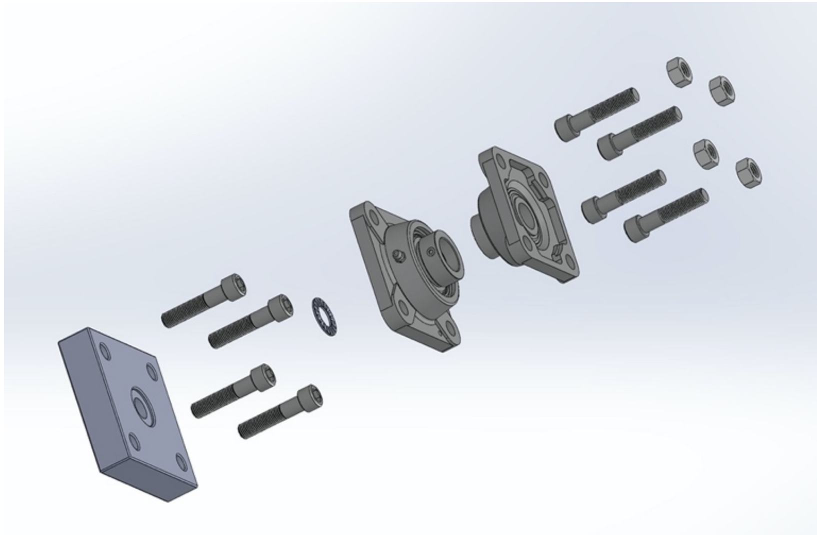

Figure 17. Exploded view of bearing subassembly.

To illustrate the axial alignment and show the normally hidden thrust bearing, the above Figure 17 shows an exploded view of this subassembly. The thrust bearing sits directly below the lower radial bearing, and in a precise countersink to allow low friction rotation with axial support.

Though both roller bearings share the same mounting hardware, dissimilar outer diameters were chosen to best address stress concentrations identified during FEA analysis. The vertical orientation of the shaft, as addressed in Section 5.1.1, does not escape the need for a highly balanced system, as small deviations from perfect mass distribution can destabilize the assembly at operating speeds. The included radial bearings are built with eccentric bearing collars, which correct for misaligned shafts in the event of poor system construction.

5.1.3 Braking System

Our braking system is comprised of the brake rotor, caliper, pads, and rotor spacer, shown in Figure 18. The rotor, pad and caliper are all based on an OEM rear braking assembly for the first-generation Mazda Miata. This was a conscious design choice to minimize unnecessary re-engineering, reduce system complexity, and remain under budget. Additionally, the use of a production component would benefit the end user in the event of maintenance with multiple public resources one could consult and aftermarket manufacturers and vendors to purchase parts from.

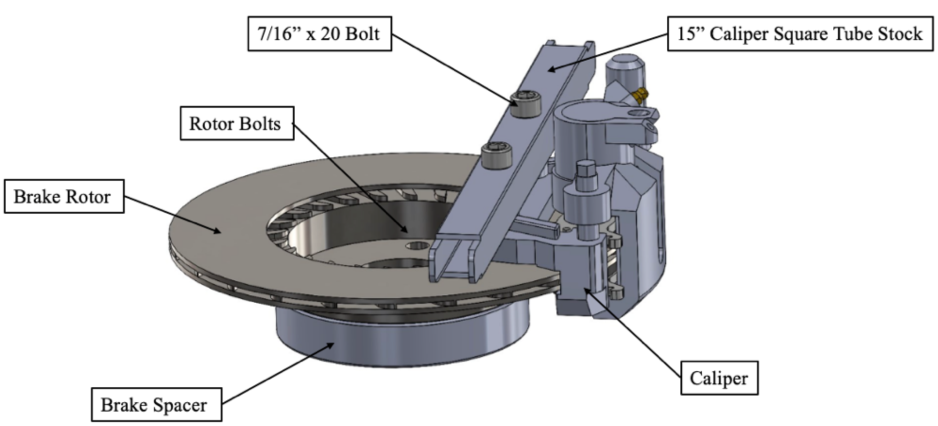

Figure 18. Braking Subassembly

The CAD uses a design sourced from GrabCAD, an open-source warehouse for user generated designs, which is consistent with the part we received. The handbrake, not pictured in the 3D model, is mounted on the exterior of the unit, in a similar location to the Control Subassembly, where it may be accessed conveniently for the user. The handbrake is intended for drift applications in rear-wheel drive cars. As this is a single caliper rather than a full axle, we believe the integrated oil reservoir is sufficient for our applications.

5.1.4 Chassis Subassembly

The chassis acts as the support system for our rotating elements, ensuring proper vertical alignment of all components, substantial robustness against possible imbalance and vibrations, and sufficient protection in case of failure. Figure 19 displays an isometric view of our chassis subsystem, with all components labeled. The steel side and top panels are not included in this image so underlying components could be seen, but our design still incorporates this extra layer of protection.

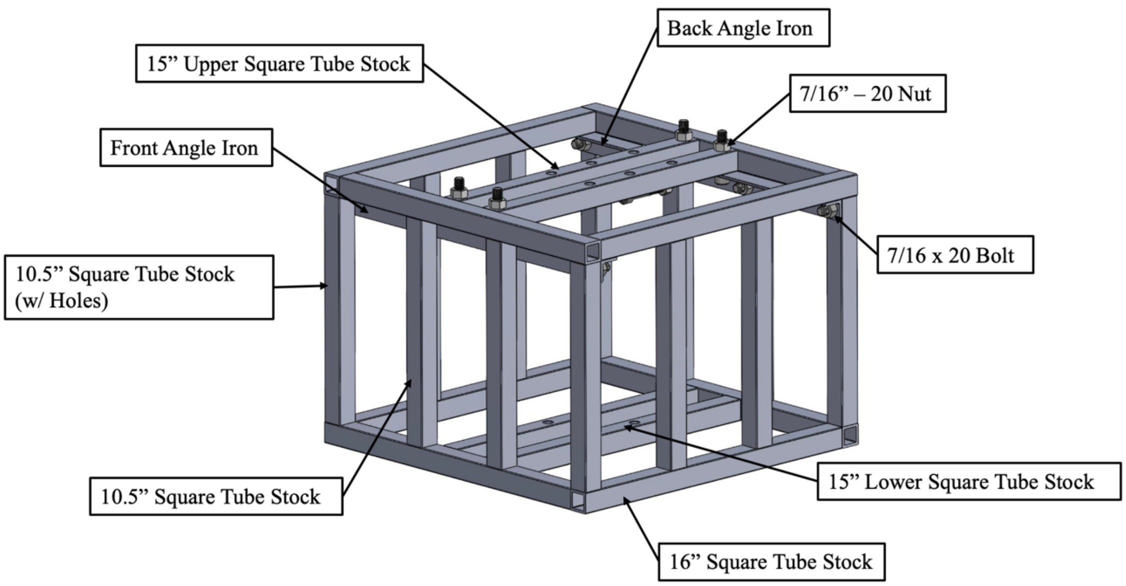

Figure 19. Chassis and frame assembly.

Most of the chassis is comprised of steel rectangular square tubing cut to differing lengths, essentially creating a cage around the large spinning masses. With a wall thickness of 1/16” and a cross section of 1”x1”, the steel tubing is robust enough to support the rotating elements inside. The bottom frame, vertical support bars, and a portion of the top will be welded together, and both angle irons and upper horizontal supports will be bolted to the rest of the chassis in order to allow for maintenance and updates during the testing process.

Beyond just the edges of our square cage, intermediary vertical supports were included to serve two purposes: keep the flywheel from breaking out of either of the sides if instability occurs and provide more connection points for the two angle irons bracing the top horizontal supports and braking caliper bar. The angle irons is bolted to the 10.5” long bars with holes in four locations.

The upper and lower bars comprised of the 15” square tube stock will provide the bolted connection for both bearing assemblies; holes are drilled into the middle to allow for this. The top horizontal supports feature a few other sets of holes, The set of four holes toward the outer edges will be used to bolt down the top steel plate. The set closest to the bearing connection point is where the motor assembly will be connected to the chassis.

5.1.5 Motor Subassembly

Figure 20 shows the motor subassembly, with the main components labeled. The motor is mounted to the chassis through a motor mounting bracket and a series of square tube stock. Instead of welding, an extra piece of 3.5” square tube stock was introduced. This allows for a bolt and nut to secure the motor mount, and for it to be detached easily. The motor connects to the flywheel shaft through a 10 mm to 20 mm shaft flexible coupler.

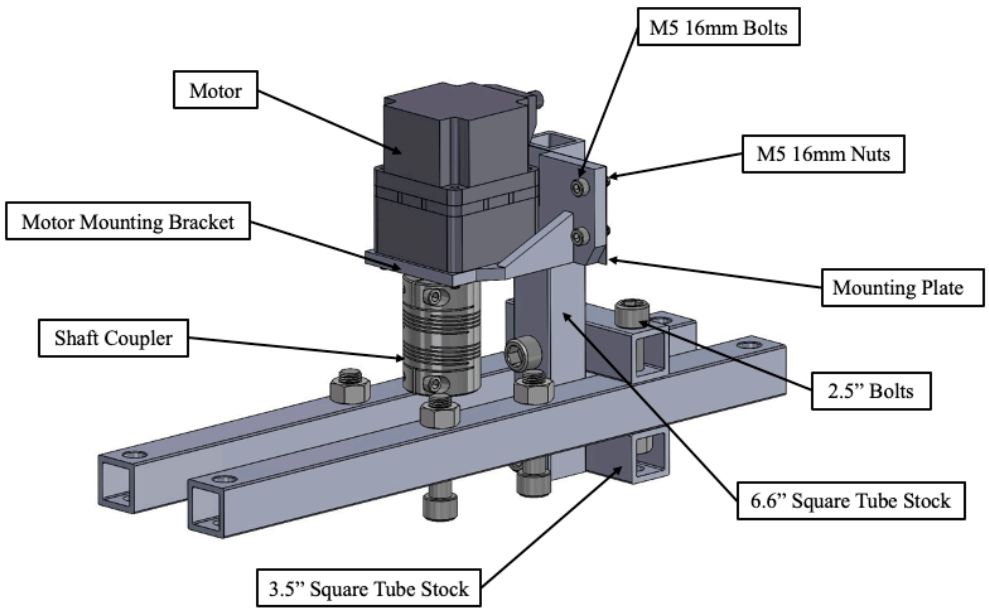

Figure 20. Motor and mounting assembly.

Overall, this design not only accomplishes the goal of being structurally sound but also is easy to manufacture and assemble. The design requires minimal welding and therefore allows for disassembly when necessary. The flexible shaft coupler permits some radial force due to vibration and flywheel imbalance without damaging the motor. The motor is mounted in a highly accessible position to provide ease of connecting electrical components.

5.1.6 Control Subassembly

The control subassembly contains all of the electrical components responsible for controlling the input and output electrical power. It includes inputs from the tachometer, RF transmitter/receiver, and button controls. The Arduino processes these inputs and changes state based on the programmed finite state machine. It contains three main states: charging, discharging, and emergency braking. Based on the current state, it will turn on and off the relays to control power flow, control the speed of the motor driver, and turn on and off the braking system.

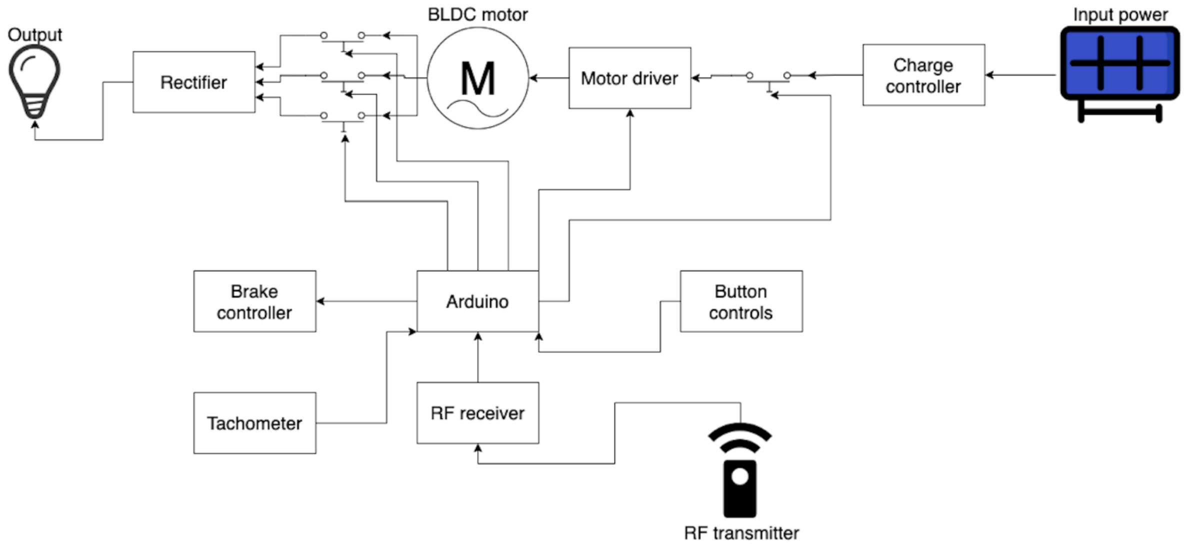

Figure 21. Control subassembly.

In the charging cycle, input power enters the charge controller and exits at 24 V DC. It passes through the relay and into the motor driver. Here it is converted into three-phase power for the BLDC motor. On the discharge cycle, the input relay is turned off and the output relays are turned on, allowing a current pull on the motor. This causes the motor to generate electricity from the mechanical energy of the flywheel. This power flows into the rectifier, where it is converted back into DC. Finally, it is delivered to the output load. The output load draws current and this determines how much energy the motor will supply. Both the maximum voltage and current will decrease as the speed of the flywheel decreases. There are no metrics available on the energy conversion efficiency, however we expect between 80-100% as BLDC motors typically are very efficient and this one is on the higher end.

5.2 Analysis of Critical Components

Engineering analysis is a crucial step in order to verify the safety and validity of any design. This section serves to outline the critical failure modes with respective load cases and calculations that were performed in order to verify our system's ability to meet design specifications.

5.2.1 Estimation of Energy Storage and Losses

Preliminary analysis for total system energy storage was initially performed under the assumption of a 10,000 RPM flywheel speed; this assumed speed was based on industry applications which run in excess of 15,000 RPM for commercial applications. After the shift in focus to a primarily research-based project rather than a market-ready solution, the size and operating parameters were scaled down to better reflect our capabilities. Further discussions surrounding safety with Mr. Pulse of the Cal Poly Machine Shops highlighted concerns over public safety in the event of failure, especially in the presence of people during the Senior Project Showcase. As a result, operating speeds have been reduced further to 200 RPM in order to maintain a public display. Due to the flywheel's energy storage function, the rotational speed scales non-linearly with total storage, so capacity has been reduced to 1/2500th of initial estimates, capping its total capacity at roughly 80J. While these results are disappointing, it is necessary to protect general welfare.

Additional losses on the system due to drag and bearings also needed to be accounted for in order to choose an appropriately sized motor and ensure the system could store energy for a sufficient amount of time. By modeling the flywheel as a stationary rectangular plate folded in on itself and subjected to airflow, the process as seen in Appendix G estimates a windage loss of 6.7 mW due to the drag on the surface of the flywheel. This value is significantly less than the initial analysis at 5000 RPM because the flow regime became laminar instead of turbulent. By dividing this windage power loss by our rotational speed and applying appropriate unit conversions, we were able to combine this with the losses calculated for the bearings, although the magnitude of windage losses was smaller and did not contribute much to the total power loss. Energy losses due to the two radial bearings and the thrust bearing were estimated using SKF's bearing friction moment model, and the combined losses due to friction was 0.069 N-m.

Table 8. Overall system's energy storage and losses.

Energy Storage and Losses	Estimated Value	Units
Flywheel Storage Capacity	80	J
Windage Losses	6.7	mW
Radial Bearing Losses	0.032	N-m
Thrust Bearing Losses	0.037	N-m
Total Torque Losses	0.069	N-m

Ultimately, the system will still be able to perform the function of storing and discharging energy, which is the critical accomplishment of our design. Furthermore, the system is able to stop in an estimated 106 seconds and hand calculations for this value can be found in Appendix G.

5.2.2 Flywheel Hoop Stress, Fatigue, and Manufacturing Errors

Our team started with the analysis of our flywheel, as that is the main driving force of the energy storage system. The hoop stress was assumed to be our critical stress, and at low rotational speeds, our design was confirmed with very high factors of safety. The maximum hoop stress of a solid spinning disk occurs at a radius of 0 where the stress is a function of the material's density and Poisson's ratio, rotational speed, and the radius of the flywheel. Full calculations are shown in Appendix H, but our preliminary calculations for our critical hoop stress produced 15.5 kPa, or a design factor of 3557, which is astronomical.

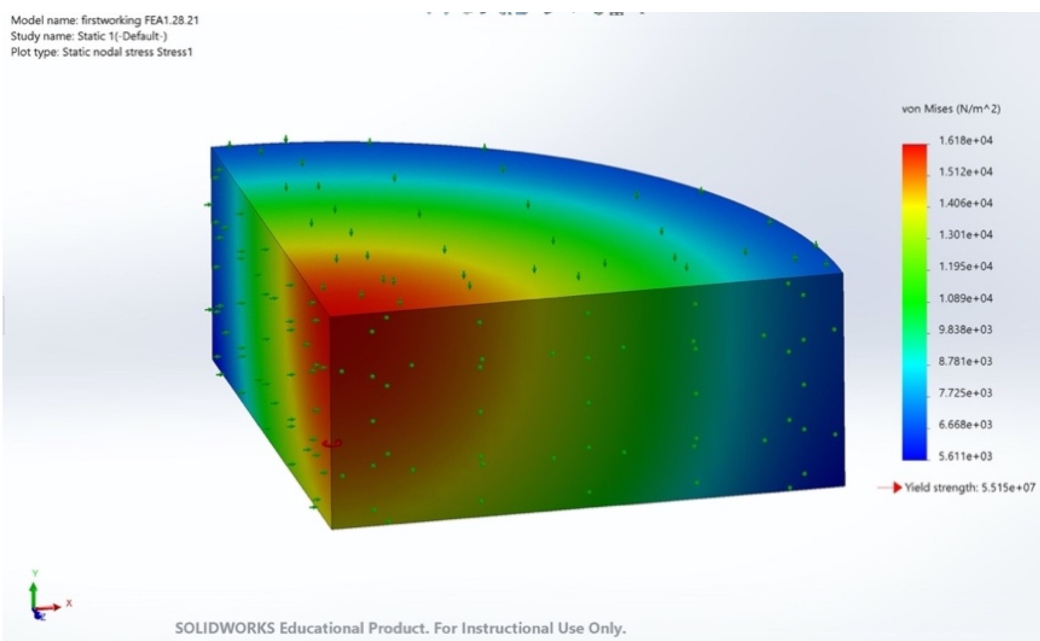

Figure 22. FEA model of von Mises stress of flywheel.

As a supplement to hand calculations, an axisymmetric FEA model was run to confirm results. As can be seen from Figure 22, the yield strength of the aluminum was well above the maximum stress, which occurred at the axis of rotation; precisely what our hand calculations predicted. Since the system will be operating at around 200 RPM, the hoop stress of the flywheel itself will evidently not be a potential problem.

In Appendix I, the fatigue life of aluminum was taken into consideration as the starting and stopping of the flywheel will effectively be loading and unload the material of the body. Unlike steel, aluminum cannot be designed for infinite life. With this in mind, our team calculated the fatigue strength over the course of 1000 cycles, which resulted in a strength of 21.3 MPa and a design factor of 1374. Although this strength is below the rated yield strength for the material, the maximum hoop stress felt was still well below that value. To alleviate the calculation even further, our team does not plan on loading the flywheel 1000 times but wanted to be conservative with the calculations.

Analysis was performed on the flywheel in order to estimate the manufacturing tolerances allowed. But what our team found was that at virtually any sizeable RPM if the center of mass was even 0.1 mm off of the axis of rotation there would be considerable centrifugal forces acting on the shaft as well as inducing high amounts of vibration. Due to feasible manufacturing tolerances being above this level, the only option would be to balance the flywheel in post processing. But as that would be extremely costly, the result is capping the maximum speed, as discussed.

5.2.3 Shaft Critical Speed, Strength, and Buckling Analysis

The shaft design went through many iterations to ensure proper support for all rotating elements. In particular, the thickness of the step supporting the combined weight of the flywheel and brake rotor was the main concern. So, a simple FEA was run through SolidWorks to confirm the strength of the steel shaft. The maximum Von Mises stress was multiple orders of magnitude under the yield strength of the material, or a design factor of 285.

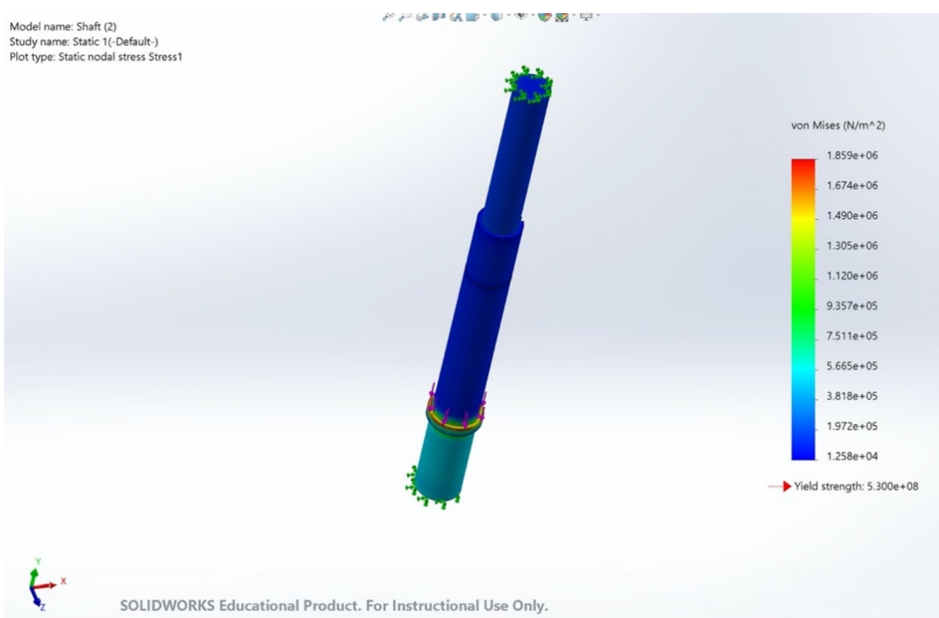

Figure 23. FEA Model of Von Mises Stress of Shaft Step

Due to the stumpy nature of the shaft, buckling was not assumed to be an issue, but the possibility was entertained as good measure. As outlined in the hand calculations of Appendix J, Johnson buckling was assumed and resulted in a critical force of 278 kN. Our total load was estimated to be in the realm of 300 N, so buckling is not a feasible failure mode.

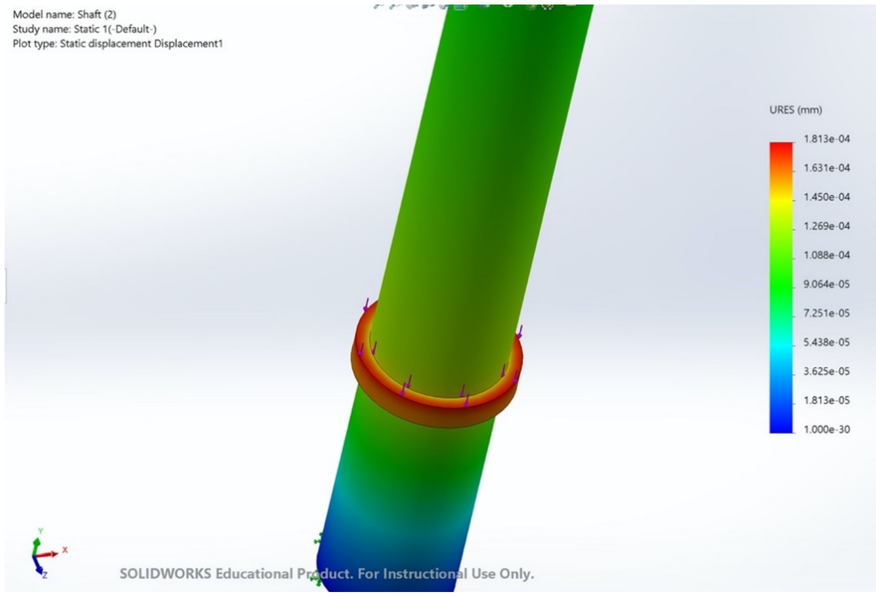

Figure 24. FEA Model of Displacement of Shaft Step

Figure 24 was included to show the deflection due to the static weight of the flywheel and brake rotor system. There was no tolerance inherent in this design that our team needed to stay under, but as can be seen the model predicts a maximum deflection of 0.0001 mm, which in essence means there will be no deflection due to the low load.

Shaft failure extends past buckling criteria and includes critical shaft speed as well. Though this concern is minimized due to the lower operating speeds outlined prior, the calculations must be executed in the event of higher operating conditions. A model of a 20mm OD shaft was used to calculate the critical speed, as this was the smallest diameter and would be the critical cross section in the event of failure. Given the current constraints with shortened shaft height, the critical speed of the shaft was 3756 RPM, resulting in a design factor of 18.7 for an operating speed of 200 RPM. These calculations can be found in Appendix K, outlining the formulation methods. The true critical shaft speed is believed to be higher, as the 20mm OD spans for only 40% of the shaft, but our calculated critical speed is a more conservative choice to evaluate the design from.

5.2.4 Machine Key Analysis

Mating the two systems described above proved to be a more difficult design challenge than initially anticipated. In the end, one of the more simplistic ways to mate a shaft and an external part was chosen – a machine key.

The machine key was the final iteration of how the flywheel would securely be attached to the shaft to prevent rotation. In order to ensure a robust system, calculations were completed and attached in Appendix L to prove the strength of the key. The load condition is worth discussing, however. Thanks to the physical way the design is laid out, if the brake rotor is to be engaged, the load will go directly into the flywheel through the brake spacer and the flywheel bolts that are threaded into the body of the flywheel. The maximum load case that the shaft key will feel is that of the maximum torque the motor could provide. The design factor for the shearing of the key was calculated to be 305, which is more than enough to prevent failure.

5.2.5 Electrical Analysis

Given that the motor accepts 30 W as input, the maximum output power that the motor is rated for is also 30 W. This will be delivered when the flywheel is at the maximum speed of the motor. Losses will occur during conversion in the motor as well as conversion in the rectifier. Unfortunately, there is no data available to calculate these losses for the components that we have chosen, but we estimate at least 80% efficiency.

The control system also requires power to collect inputs, produce outputs, and operate the finite state machine. Although these values will be important to minimize in a final product, it is unnecessary to pay attention to them for the prototype build. The control system power consumed will stay constant when the flywheel size and speed is eventually increased in a product build, which will then be minimal in comparison.

5.3 Material and Part Selection Justification

Selection of the components was one of the more difficult aspects of this project. Due to low manufacturing capabilities and little industry common practice guidelines to go off of, some aspects of the design were driven by the availability of these components. Analysis was completed on components where more obtainability was less of a problem, and decisions were made off a variety of factors – cost, strength, manufacturing time to name a few.

For the main component of the system, and the most difficult to source, the design includes a 14" solid aluminum flywheel. When balancing other options of more dense materials that were only available at smaller diameters, the larger diameter was able to store more energy due to the increased mass moment of inertia. Composites were considered as well, but as per the recommendation from Dr. Noori, due to delamination and difficulty of manufacturing it was in our best interest to use a solid piece of dense material. The idea of using steel rod inserts inside the aluminum disk towards the outer diameter to increase the total energy storage capacity was also considered but ultimately deemed unnecessary due to large manufacturing difficulties and minimal increase of energy storage.

One of the integral components in our design is the motor. The motor serves as the main system for energy conversion. In the charging state, electrical energy is converted to mechanical energy to spin the flywheel. Since we decided on a permanent magnet motor, this same motor can be used as a generator when a load is attached, converting mechanical energy back into electricity. We chose a brushless DC motor (BLDC) with a 5:1 gear ratio since it also has a high torque, power efficiency, and small size compared to other motors. The 5:1 gear ratio will also allow us to spin the flywheel at a lower speed while still getting an efficient power conversion from the motor.

The orientation of our flywheel lends itself well to low loads into the radial bearings and the majority of the load into the thrust bearings. This was intended as the purpose of thrust bearings are to support an axial load, and radial bearings for support. Obviously, the frictional losses of the bearings were calculated to be lower the lower the loads acting on them are. There most likely will not be high variability in load due to speed on the thrust bearing, but the radial bearings will have high load volatility as the RPM increases. At the lower RPM's we intend to test our prototype, the bearings chosen are up to specification and will induce a lower friction loss coefficient to the system. The two radial bearings will be purchased will a four-bolt flanged housing to ease of assembling. The thrust bearing on the other hand will require a custom housing to be machined and implemented but will be machined from a small block of aluminum for ease of manufacturing.

Our team will be ordering the shaft from Misumi, a custom shaft vendor. This decision was made to relieve part of the manufacturing process and because of the competitive cost Misumi offers. For strength and stiffness reasons, the shaft will be manufactured out of 1045 carbon steel. Detailed design was performed for the shaft to ensure key criteria was within reason. The strength of the material was chosen for low deflection and high strength. As if any sizeable deflection occurs due to imbalance during operation, the loading will escalate as the center of mass will be then further from the axis of rotation. The shaft will not be in danger of buckling, and critical speed calculations were performed to confirm the system will never reach that maximum physical RPM.

To ensure safe operation of the flywheel assembly, the design includes a braking system to be used in an emergency. The rotor and caliper for the braking system specified is from a Mazda Miata. Which is in part because of its high energy dissipation, or high stopping torque, but additionally because of its weight. This is a special situation where the weight included is desirable in the system as a whole as it increases the total energy storage at any given RPM. In case of a system malfunction, a mechanical handbrake gives the operators the ability to bring the flywheel to a halt even if the controls system goes down. In order for there to be enough clearance between the rotor and the flywheel, and custom spacer was designed to fill the crucial gap demanded. Again, for ease of manufacturing aluminum was chosen as the material for this component.

Though many ideation sessions and conversations with outside sources, the final design depicts the brake rotor being mounted directly to the flywheel itself. Previous designs contained systems where the brake rotor and flywheel were individually attached to the shaft, but because of high load flow through the shaft and tight fit of components, it became clear it was necessary to connect the load transfer to exactly what was resisting the brake. Based on the assumption that the bolt spacing pattern was designed using appropriate safety factors, additional bolt shearing calculations were not necessary.

Through the shaft and the bearings, the flywheel will be connected to the chassis. This was aptly named as it supports the main component of the system and will be mounted to the ground. As seen in the CAD, there is a frame built out of metal square tubing and shields the flywheel from the outside using steel plating. This was an important design choice for safety, to make sure there are no pinch points and to make sure if the brake is engaged the chassis won't start to spin with the flywheel itself. This box was created to be as small as possible and encases all the internal components that can cause harm. The second job of the chassis is to support the motor mounted on top, where the electrical power flow will be directed to.

5.4 Safety, Maintenance, and Repair Considerations

A large spinning mass, even at the drastically lowered speed, still poses major safety concerns. To mitigate these hazards, we have put considerable thought into the housing our system will be contained in. The frame itself has vertical bars that not only provide extra support for the whole system but also work as a safety precaution in case of some failure with the shaft or bearings; the spacing between these vertical bars ensure that the flywheel would not be able to break out of the sides. To further enclose the system, steel plates will be welded or attached to all sides of the frame to reduce all pinch points and contain any ruptures.

While welding all elements ensures a solid and strong connect, welding does not allow for easy removal for maintenance and repair, which will be necessary for the testing process. The majority of the frame, chassis, and steel sidings will remain fully welded, but the top cross bars as well as the angle irons will be bolted to the rest of the frame to allow for removal. Without the bolted connection, the shaft and its attached components (i.e. flywheel, brake rotor, and brake caliper) could not be removed from the system.

A strong, structurally-sound chassis is not enough to ensure safe testing; the chassis must also be fully secured to the ground to mitigate any risks due to the system's vibrations. Spare steel sheets will be used to create four 90˚ bends that will be welded to the steel siding, two on a pair of adjacent sides. Depending on the strong floor's specifications in the Structures and Composite's lab, holes will be drilled in each bend to allow four connection points to the steel rails embedded in the lab's floor.

5.5 Structural Prototype

The goal of the structural prototype was to demonstrate the main function of our system, namely storing and releasing energy from a rotating object with considerable inertia. For the demonstration, the structural prototype consisted of a bike wheel and tire that was driven by a DC motor, all connected through a 3D-printed coupler as seen in Figure 25.

Figure 25. Structural prototype.

The DC motor was connected back to a 12 V motor controller and terminates in an Arduino Mega. The motor, though small with a rated output of 12 V, could spin the bike tire quite effectively and demonstrated the ability of a motor to spin a flywheel-like object. More critically, the system must pull that same energy out, which would be measured by an LED connected in series with the DC motor. Once spun up to 60 rpm, the motor input power was disconnected and then measured with a multimeter.

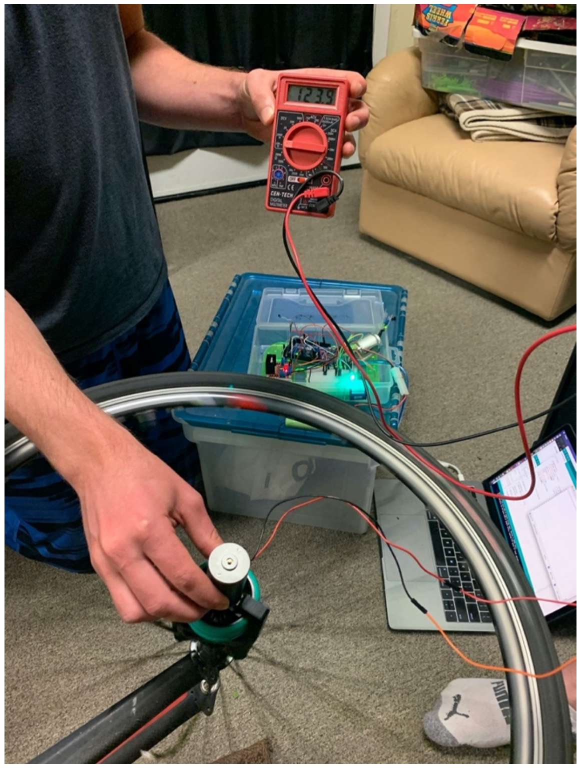

Figure 26. Structural Prototype outputting Power

Through this experiment, it was proven that the same motor could both charge the system and generate power by discharging the system without having to reverse the direction of the motor, outputting a voltage of 124 mV. Since this small motor has a nominal speed of 8000 rpm, the output was only a fraction of the possible power generated. To get close to the complete 12 V potential output voltage, it would be necessary to include a gear system, something which we will incorporate into our final design.

5.6 Cost Analysis

Our preliminary cost estimate put us at the very top of our budget, and with some other added design decisions since then, sourcing for components needed to be modified. For the shaft, after the flywheel seat was dramatically reduced in diameter, the customized rotary shaft from Misumi went down in price to around $50. For most of our steel and aluminum needs, we decided to source raw materials from McCarthy Steel, a local steel distributor, instead of McMaster, which might have everything we need but is expensively priced and the shipping costs for the weight of our parts would push us outside of our budget.

Table 9. Verification prototype cost analysis.

Components/Subsystems	Approximate Cost
Shaft	$50
Aluminum Flywheel	$350
Full Frame with Side Panels	$170
Braking System	$220
Bearings and Bearing Housings	$230
Motor and Related Components	$550
Control System	$61

Without taxes and shipping fees (when applicable) taken into account, our current verification prototype cost is around $1,700; a more detailed breakdown of these costs can be seen in the final budget sheet as seen in Appendix M.

5.7 Remaining Concerns

Currently, our concerns relate to satisfying the expectations of our sponsor and a few mechanical issues. We want to ensure that we are creating the best possible system as our sponsor, Mr. Bhutani, has graciously funded our project. With the decreased operating speed due to safety concerns, the data from our tests will not be anywhere near our initially expected energy storage capability. Everything designed into this system has the capability of running at an RPM in the 1000s, but this constraint is almost entirely due to the balancing of the flywheel system, which leads into the team’s next concern.

Balancing the flywheel is something that every high rotational speed system has to undergo. As no manufacturing process can be precise enough to get the center of mass exactly on the axis of rotation, post processing is needed in order to do so. But finding a machine that can complete this process for a flywheel assembly as large as ours might be a problem. At this moment in time, we are continuing assuming we will not be able to get our flywheel balanced and operating at low speeds safely with minor balance issues.

Obviously, these considerations will then affect the total power stored. We are planning to power an LED for an extended amount of time since an LED has low power consumption. The main concern here then is if this test will be enough to viably prove we can store reasonable energy. We believe so, but more consideration will be needed in this area. Due to project time constraints, no in-depth analysis will be done to scale results. However, we will spend time discussing how our test results verify our concepts later in this report.

As it stands, the current brake caliper included in the 3D model is the brake sub-assembly from a 2002 Mazda Miata. Between the NA and NB generations of Miatas, 1989-1997 and 1999-2005 respectively, the subframe, suspension components and exhaust system remained the same. We believe that the caliper modeled is a direct translation of the 1996 model caliper, however, we are slightly concerned that the two will be different. Some concern stems from the caliper being an OEM replacement part, which can lend itself to being designed with different proportions and specifications. We do not believe that the mounting locations will be inhibited, but that the caliper’s overall footprint may conflict with current housing limitations. To address this concern, we will wait to fully weld and cut portions of the frame and steel sidings until the brake is received and can be fitted to the system.

6 Manufacturing

The verification prototype of our scaled down system can be broken into six separate subassemblies – flywheel, braking, bearing, motor, chassis, and control system. The subsections below go into further detail on how all materials and components are procured, the necessary order of manufacturing operations taken, and how all components and subassemblies are assembled into a final product. Additionally, the complete drawing package is included in Appendix N.

6.1 Flywheel Subassembly

The flywheel subassembly, critical to our energy storage capacity, consists of a 14” aluminum round, steel shaft, shaft key, and retaining ring. The aluminum flywheel was purchased from a local supplier McCarthy Steel Fabrication, the retaining ring and shaft key were procured from McMaster-Carr, and the steel shaft was custom machined by Misumi.

Before drilling the center and tapped holes, a CNC mill was used to prepare the aluminum round was for future manufacturing steps. Both the top and the bottom of the aluminum round needed to be faced in order to smooth out any rough edges from the raw material.

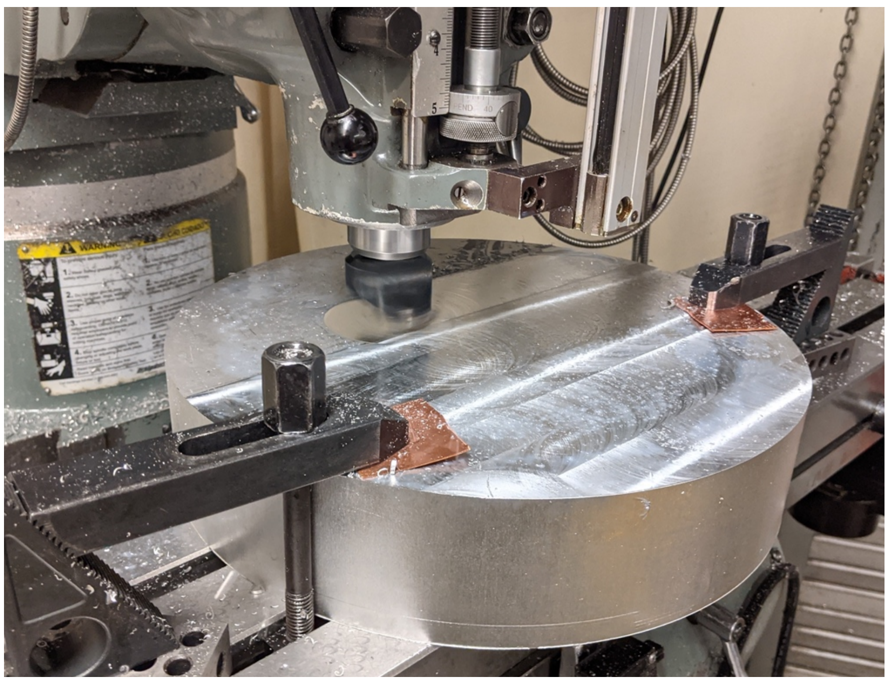

Figure 27. Facing of aluminum round.

Pilot holes for the four-bolt pattern and the true center of the disk were then drilled to reduce possible eccentricity once in motion and align hole locations correctly. Drilling and tap operations were then completed to accommodate the M12 x 1.5 bolts mounting the flywheel, brake rotor, and spacer together. The flywheel center was bored out in preparation for the press fit with the shaft later on in the assembly process.

Figure 28. Tap operations for flywheel's four bolt pattern.

To further constrain the flywheel and shaft's motions, the flywheel was keyed with a 3mm channel taken out of the internal radii. The Mustang '60 Machine Shop has limited options for keyway sizes and equipment to support the process, so help was needed from elsewhere. Professor Trian Georgeou from the Cal Poly IME Department assisted with the process of broaching the keyway in the part.

Ordering the shaft through Misumi allowed for large amounts of customization, but the shaft still had to go through further modifications. Misumi had defined ranges of sizes the steps in the shaft could have, but these ranges did not perfectly align with the intended design. The shaft size was ordered to allow for the least amount of manufacturing in the shop once delivered. Additionally, any shaft design features through Misumi had to be radial whereas the keyway was not an option available from Misumi. Using a conventional lathe, the largest radius of the shaft was turned down to a 25mm OD to ensure proper mounting between the flywheel and shaft. The retaining ring slot was turned down towards the top of the shaft with the lathe. Finally, a keyway was machined with a mill to mirror the flywheel's slot along the length of the central step.

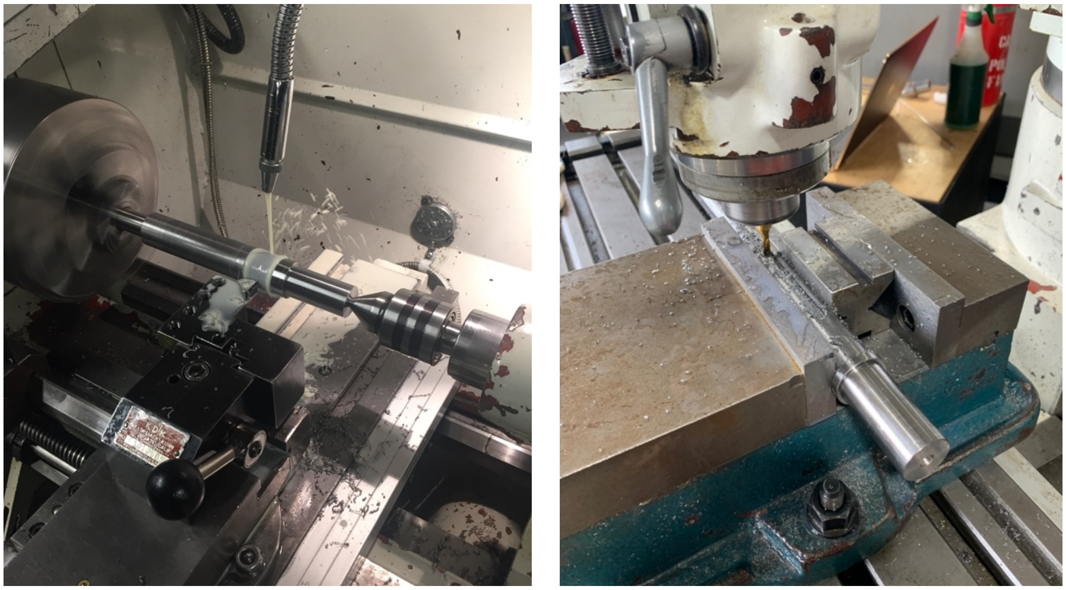

Figure 29. Machining of retaining ring slot (left) and shaft keyway (right).

The flywheel assembly will start with the shaft key being slotted into the shaft's keyway. Next, the aluminum disk will be press-fit onto the shaft using the hydraulic press in Mustang '60, making direct contact with the shaft's seat. After this assembly joins with the spacer and brake rotor from the brake subassembly, the retaining ring will be finally affixed to the shaft, securing both assemblies together.

6.2 Braking Subassembly

The braking system is composed of a brake rotor and caliper, rotor spacer, rotor bolts, brake fluid, a hydraulic handbrake to operate the brake, and associated brake lines to transmit the fluid. The rotor, caliper, brake lines and brake fluid were all procured from Summit Racing, whereas the handbrake and spacer and bolts were purchased from Amazon and McMaster-Carr respectively.

For the brake spacer, the disk was first center drilled with a 25mm cross-section on a CNC mill. Following this operation, four 11.5mm ID holes were drilled in a circular pattern at a centerline diameter of 100mm. This operation was also completed on the mill, as reference to the center-hole is critical to the holes' positioning. Lastly, the spacer underwent a slight chamfering on the CNC mill along the external edge and internal holes to ease with assembly and reduce any burrs.

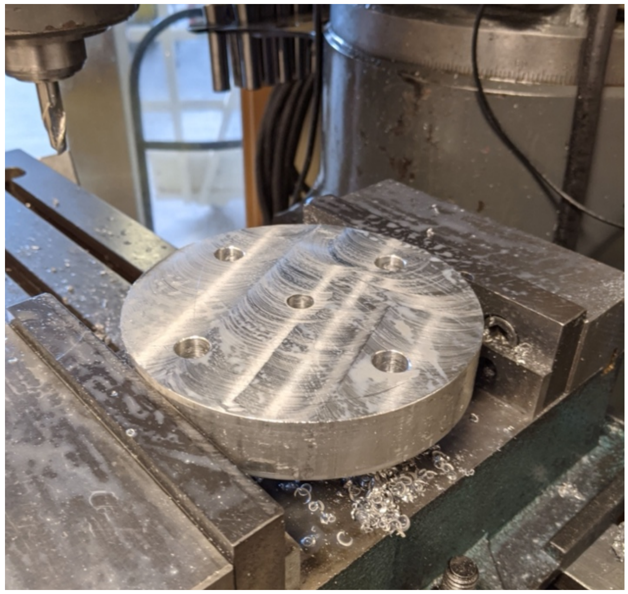

Figure 30. Machining process for brake spacer holes.

Once the flywheel subsystem was properly placed and attached to the bearing sub-assembly, the brake spacer was press-fit onto the shaft while paying careful attention to the clearance holes' alignment. Following the spacer, the rotor was affixed to the spacer and flywheel using the rotor bolts to complete the rotational member. The caliper was then mounted to an internal support bar using two threaded bolts to tap into the pre-threaded holes typically employed in its automotive application. The handbrake could then be attached to the exterior of the unit using four bolts and nuts sent through the steel surrounding. The brake lines were routed between the caliper and handbrake, with proper fittings attached to each end. To ensure the effective operation of the system, the handbrake oil reservoir was filled with brake fluid and bled to purge any air in the line.

6.3 Bearing Subassembly

The bearing system is comprised of two roller bearings seated in four-bolt housings, with 20mm and 25mm shaft openings respectively, a needle thrust bearing, a thrust bearing housing, housing mounting bolts and bearing oil. The roller bearings, mounting bolts, bearing oil, and raw material for the thrust bearing housing were all procured from McMaster-Carr; the thrust bearing was purchased from Motion Industries.

The thrust bearing housing was the only part requiring further modifications, which were all executed on a mill as positioning and accuracy is of the utmost importance. The bar stock was center drilled and counterbored to accommodate the correct seating of the thrust bearing, and the block had four bolt access holes drilled to align with the radial bearing housing's mounting pattern. To ensure an extremely smooth surface finish for the thrust bearing to glide upon, the housing was put on a lathe using a four-jaw chuck to smooth the rough surface left by the boring bit.

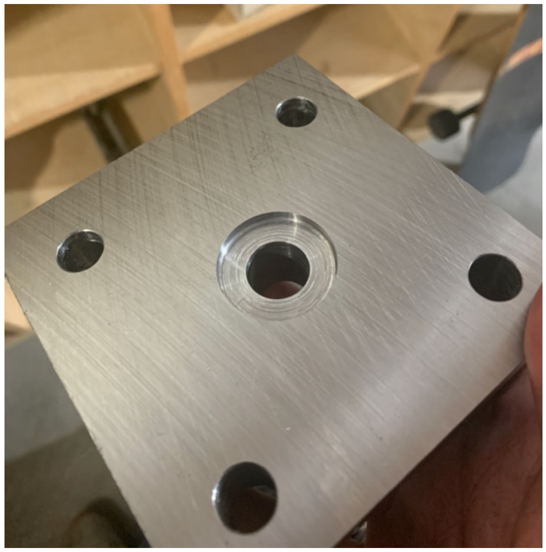

Figure 31. Finished product of the thrust bearing housing.

The bearing subassembly started with the thrust bearing housing being seated on the bottom crossbars and properly aligned with the mounting holes. The thrust bearing was then placed in the counter-bore and lubricated with the bearing oil. Next, the lower 25mm radial bearing assembly was situated atop the thrust bearing housing and secured through the housing and lower crossbars using the four mounting bolts and nuts. The flywheel assembly was then seated vertically in the 25mm opening, and the upper 20mm bearing housing was mounted to the top of the shaft. This housing, similar to the lower housing, was bolted directly into the supporting crossbeams running along the roof of the unit.

6.4 Motor Subassembly

The motor was purchased from Oriental Motor due to their wide supply of BLDC motors and flexible specifications of rpm, torque, and gear ratio. A matching motor driver, mounting bracket, and shaft coupling were purchased here as well. These components came ready to be assembled and integrated into our prototype. Although more expensive than other options, this motor came with the correct rpm range, a higher torque ratio, and higher efficiency. If we selected a cheaper motor, we would most likely also need to purchase a planetary gearbox and a driver that would not provide as many motor features, such as a speed output, variable speed capability, and adjustable acceleration/deceleration time. The shaft coupler will connect to the main flywheel shaft, and the motor driver will connect to the Arduino and charge controller.

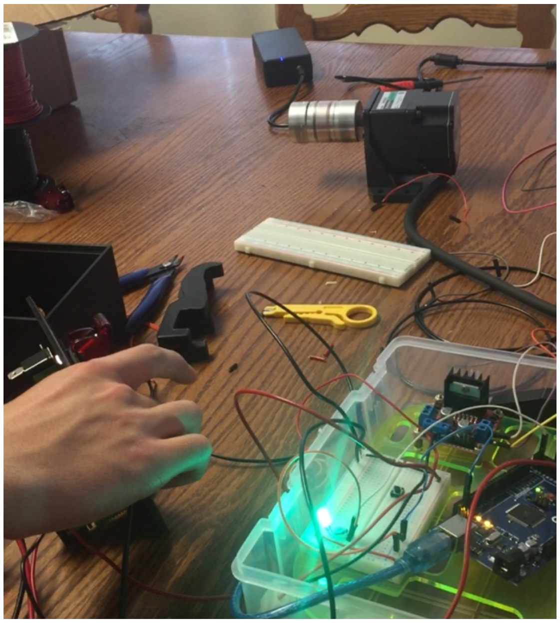

Figure 32. Motor connected to driver and inputs

The motor purchased came with a mounting bracket that was used to connect the motor to the frame. The extra 1”x1” steel tubing was cut using a chop saw and ground to the correct length. Then, holes were drilled in the three supporting members to be bolted onto the chassis itself. A steel plate was welded to the vertical member and included the bolt pattern that mirrored the motor mounting bracket, as seen below.

Figure 33. Weldment of motor mounting plate to frame member.

6.5 Chassis Subassembly

The chassis is comprised of rectangular steel tubing with a 1”x1” cross section and a wall thickness of 1/8”, each cut to different lengths as specified in our part drawings. Tubing was all purchased from McCarthy Steel, a local steel distributor, and was priced by the foot. To further support elements without completely welding the system together, angle irons are also being used at the top of the frame. These low carbon steel angles have a height and width of 1” and a 1/8” wall thickness, also procured from McCarthy Steel.

Each steel tubing piece for the frame was manufactured the same, with the exception of their overall length and the drilling of 11.5 mm diameter holes; there were 24 bars in total. First, a vertical band saw will be used to cut the steel bar stock to the correct length. The newly cut edges, along with a couple inches on each face of the bar, were be cleaned and smoothed out with an angle grinder to insure a clean, flat surface for the welding procedures later on. Both angle irons were cut and drilled in the same fashion.

Figure 34. Angle grinding process for all steel tubing bars.

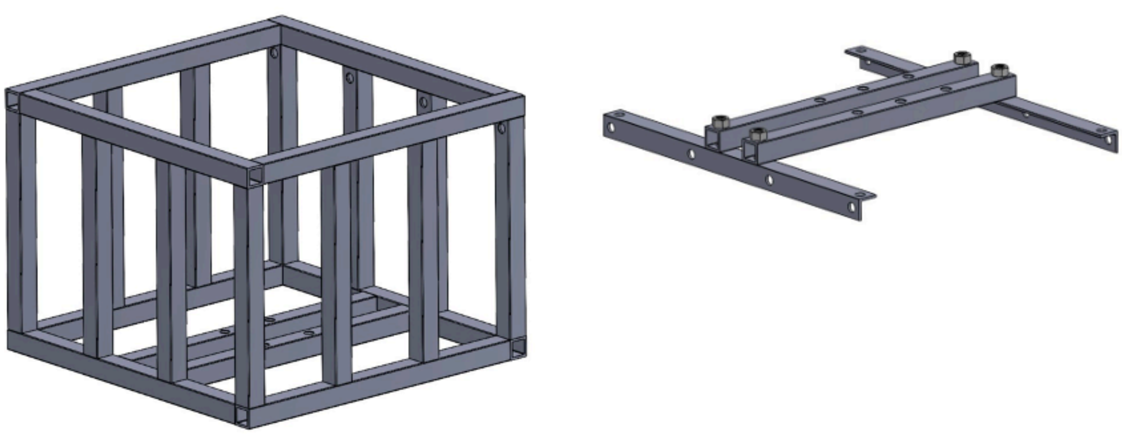

Figure 35. Main welded frame of chassis (left) and removable top portion of chassis (right).

Assembly for this chassis was split into two pieces, as shown in Figure 35. The main welded frame was assembled from the bottom up with the help of a student Shop Tech from the Mustang ’60 Machine Shop. Bars were first spot welded together to ensure alignment and right angles as specified in the weld drawings. After final check of dimensions from the team, the bars were then welded all the way around.

To avoid fully welding our system together and severely limiting our access to internal components during the testing phase, the top section of the chassis is separately bolted to the main welded frame.

Figure 36. Finger break in use cutting side panels

The steel siding was cut to size using a finger break, pictured in Figure 36. These sheets were then welded onto the frame for extra protection. The scrap from this process was used to secure the flywheel assembly to the strong floor by welding 90-degree bends to the outside of the chassis and then bolted with T-slot nuts, as seen in Figure 37.

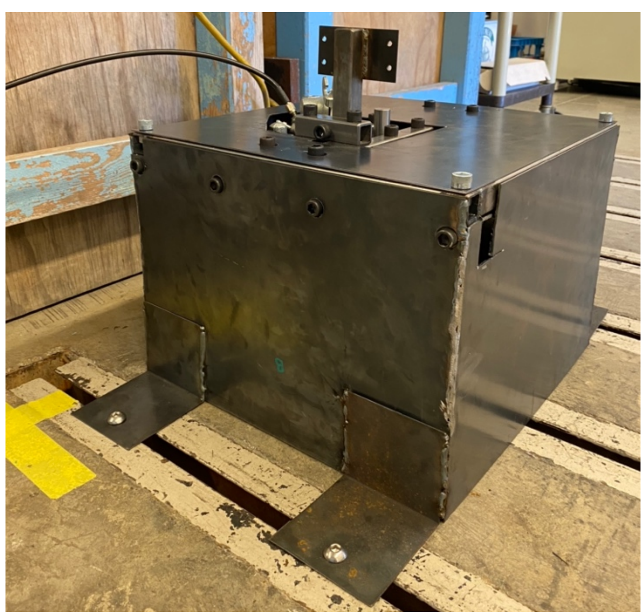

Figure 37. System attached to strong floor with manufactured 90˚ bends.

6.6 Control System Subassembly

Most of the electronic components were purchased from either Amazon or Sparkfun. All of these did not require any manufacturing but will mainly required assembly. All wiring had to be connected correctly according to the datasheet of each module as specified in Appendix N. Each component was connected by either soldering or connecting header pins. This system operates with an Arduino Mega, processing inputs and then providing the correct outputs. The Arduino is connected to three inputs that it will monitor, the tachometer, the button controls, and the rf remote controls. Based on these control inputs, the Arduino program changes state from charging or discharging and controls the output modules. The Arduino outputs are used to turn on and off relays for system power output, control the motor driver, and engage or disengage the braking system. The Arduino code can be found in Appendix O.

Figure 38. Control system input panel.

6.7 Final Assembly

Starting with the welded portion of the chassis subassembly, the lower roller bearing and thrust bearing housing were bolted onto the bottom square frame. The shaft assembly, as described above, needed to be done in pieces to fully construct the final system. A secure and effective press fit of the flywheel could potentially damage the lower bearing assembly and aligning a couple hundred-pound piece into a small space proves to be very difficult. For these reasons, the shaft and the press-fitted flywheel were seated within in the lower bearing assembly followed by the spacer, brake rotor, and retaining ring.

Since the brake rotor caliper is mounted by its top and not its side, a horizontal supporting bar was designed to extend across the top removable portion of the chassis. For a stronger connection, the caliper support bar was spot welded to both angle irons, and after the correct placement is determined, the support bar was fully welded. The angle irons were then bolted to the chassis' vertical supports at four connection points each to ensure maximum stability. The two top cross bars were bolted to the angle irons, and the upper bearing housing was screwed into these cross bars using four cap head screws.

6.8 Budget Status

From the previous budget estimates during CDR, our budget has largely remained unchanged with a few notable exceptions. In comparison to an original budget of $1,250 for the project, the total current cost is $1,989.33. The difference between the two figures was in part due to higher than anticipated metal costs for the aluminum flywheel disk as well as core charge costs associated with the braking components. An additional contributor is a $150 service charge for a shop technician from the Cal Poly Machine Shops to weld the chassis, which is significantly more cost effective than other options ranging around $500 for similar work. Despite these additions, the project is still within the original allotted funds of $2,500.

Table 10. Summary of current project budget

Subassembly	Part Cost	Shipping & Tax Cost	Projected Cost	Actual Cost
Flywheel	$431.92	$19.00	$450.92	**$502.91**
Braking	$208.42	$58.62	$267.04	**$218.35**
Bearing	$209.40	$20.04	$229.44	**$229.44**
Chassis	$183.51	$4.00	$187.51	**$332.00**
Motor	$557.84	$3.00	$560.84	**$560.84**
Control	$117.34	$28.45	$145.79	**$145.79**
Total	$1708.43	$133.10	$1841.54	**$1989.33**

7 Design Verification

With a shift in the focus from our detailed design, the full-scale model specifications outlined early in this this report are no longer applicable to our verification prototype centered around a simplified and scaled down system. For this reason, we have created a new specifications table to evaluate our prototype, outlined in Table 11. This specification table outlines the benchmarks our system was intended to meet, along with critical threshold values, their tolerance, ability to impact system performance, and what each specification achieved.

Table 11. Verification prototype specifications.

Spec. #	Specification Description	Requirement or Target (units)	Tolerance	Risk	Compliance
1p	Maximum power output	30 W	Min	H	T, A
2p	Sustained power output	0.03 W	Min	H	T, A
3p	Noise measurement	30 dB	Max	M	T
4p	Weight	300 lbs	Max	L	I
5p	Manufacturing cost	$2,500	Max	M	A
6p	Power loss	100% per 30 min	Max	H	T, A
7p	Storing capacity	100 J	Min	H	T, A
8p	Charge time	5 min	Max	M	T, A, S
9p	Brake Time	5 seconds	Max	M	T, S

As mentioned previously in Chapter 3.4, each of these columns address specific goals of the system. To the left, 'Specification Description' identifies the feature to be assessed followed by the measurable goal in the following column titled 'Requirements'. The 'Tolerance' column categorizes the requirement as a limit to surpass or remain below and the 'Risk' column specifies the severity of the feature by denoting (H)igh, (M)edium, or (L)ow. Finally, the compliance column denotes the type of compliance necessary for each specification with (A)nalysis, (T)esting, (S)imilar, and (I)nspection.

Ultimately, it is our intention that any results we found can be scaled up and prove the feasibility of a flywheel energy storage system on a larger scale. The prototype specifications allow for a safe, scaled down prototype while still demonstrating the efficacy of the system. After testing the system against our specification table and recording various metrics, we are now able to calculate the efficacy of our full-scale design.

Testing was carried out in Cal Poly's Structures and Composites Lab in 197-135. The flywheel system was bolted down to the strong floor using T-nuts and was connected to the control system. This control box wires were extended to a safe distance. This setup can be seen in Figure 39. Over the course of two main testing days, we were able to perform all seven tests under the guidance of lab assistant Colin Harrop and Dr. Schuster, who acted as our faculty observers. The user's manual, all test procedures, and completed Design Verification Plan and Report can be found in Appendices P through R.

Figure 39. System and operator test set up on Strong Floor.

7.1 Maximum Power Output (Test #1)
It is important to know the amount of power the system can supply instantaneously because it will determine what appliances the final design can power. The system should have the capacity to provide a larger output when necessary, but just for a shorter period of time.

In order to verify the system meeting Specification 1p, we tested the system's maximum power output. A resistor was first connected to the output terminal, and multimeters were placed in series with and parallel to the resistor in order to measure output current and voltage respectively. The flywheel was then charged to 200 rpm and switched to discharge cycle. The test current and voltage at the beginning of the discharge cycle were recorded, and the output power was calculated. Results for trial can be seen in Table 12.

Table 12. Results of maximum power output test.

Trial	Current, I [A]	Voltage, V [V]	Output Power, P [W]
1	2.98	12.00	35.76

All measurements were from a multimeter with a precision of 3 significant digits, so the associated uncertainty for each measurement was calculated. Additionally, since the output power was calculated with measurements, an error propagation calculation was also necessary. The power uncertainty due to error propagation from computation was 0.1152 W. Both calculations can be found in Appendix T.

7.2 Sustained Power Output (Test #2)
Next, we measured the sustained output power. This test showed how long the energy storage system can sustain a desired power output. For this test we chose an output of .03 watts, an estimate of how much power a basic LED takes to operate. Choosing too high of an output would have drawn on the flywheel in such a way that would not have let us see the longevity of the test due to the 80 J of calculated time, so an LED was an elegant choice.

The system was tested in three separate trials, with each trial lasting 15 seconds. If the system was able to maintain a .03 W output or greater during the test duration, the trial was considered a pass. Results for the Sustained Power Output test can be found in Table 13.

Table 13. Results for sustained power test.

	Trial 1	Trial 2	Trial 3
Test Pass? (Y/N)	Y	Y	Y

7.3 Noise Measurement (Test #3)
Noise testing with a decibel meter was needed to verify the prototype's satisfaction of Specification 3p. In comparison to the ideal design, our significant changes with bearings, speed, and housing render this data not easily scalable. However, this was still worthwhile information to collect with regards to the efficiency and operation of the flywheel.

Our team was unable to procure a decibel meter, so the phone app *Sound Meter* was used instead. After connecting the power supply to the system, the maximum decibel readings were taken for each trial at varying increments of 25 rpm until the maximum speed was reached. The readings for each of the three trials are tabulated in Table 14.

Table 14. Results of noise measurement test.

Operating Speed [rpm]	Decibel Reading [dB]		
	Trial 1	Trial 2	Trial 3
200	27.6	28.1	27.3

7.4 Power Loss (Test #4)
Specification 6p addresses the power loss associated with the system, which was tested by determining the total length of time the system can dissipate charge to a load without any additional power input. This test is particularly important because the simplified and scaled-down build introduced frictional losses from the bearing system.

To begin this test, the system was spun up to the operating speed of 200 rpm for 60 seconds. Then, the power supply was disconnected whilst a stopwatch timer was started. The time was stopped once the flywheel completely stopped spinning, and the test was repeated two more times. The pass criteria for this test was at least 30 minutes of spinning after the power supply was disconnected. Test results are shown below in Table 15.

Table 15. Results for power loss test.

	Trial 1	Trial 2	Trial 3
Test Pass? (Y/N)	N	N	N

The benchmark for power loss was set months prior to receiving the bearings, when the system was expected to have substantially lower frictional losses. This disparity is further addressed in Next Steps Chapter 9.3.

7.5 Storing Capacity (Test #5)
An important aspect of the system is its ability to store energy, as covered in Specification 7p. This test determined the total amount of energy the prototype can hold given our maximum operating speed. After first fully spinning up the system to 200 rpm, a load in the form of a LED was connected to flywheel whilst starting a stopwatch. Readings were then taken from the multimeters every 2 seconds and recorded. The stopwatch was only stopped once the LED turned off, and the total power output at each time was then calculated. The test results are displayed in Table 16.

Table 16. Results for storing capacity test.

Time, *t* [sec]	Current, *I* [A]	Voltage, *V* [V]	Power, *P* [W]
0	2.98	12.00	35.76
2	2.08	10.97	22.82
4	1.75	10.21	17.87
6	1.47	9.16	13.47
8	1.29	8.57	11.06
10	0.85	7.24	6.15
12	0.96	6.68	6.41
14	0.39	5.76	2.25
16	0.22	5.05	1.11
18	0.06	4.19	0.25

7.6 Charge Time (Test #6)

The sixth test studied the time for the flywheel to spin up to maximum operating speed. Covered in Specification 8p, the charging time is critical to ensure any input power can be converted to stored kinetic energy effectively.

If the flywheel was able to reach full operating speed given the maximum input power within 5 minutes, this was considered a pass. Any length of time beyond 5 minutes was a failure. Our recorded data for the flywheel charge times can be found below in Table 17.

Table 17. Results for charge time test.

Flywheel Speed (RPM)	Charge Time, *t* [sec]		
	Trial 1	Trial 2	Trial 3
250	150.2	150.7	150.8

7.7 Brake Time (Test #7)

Finally, we ensured that the flywheel system can come to a complete stop in the event of an emergency in a reasonable time period. Outlined in Specification 9p, this braking test was critical as safety of the operator(s) and others is of utmost importance.

To complete this test, the system was spun at 60, 100, and 200 rpm. The braking system was fully engaged for three separate trials at 200 RPM, and single trials at 60 and 100 RPM, resulting in five total trials. Once engaged, a stopwatch was started until the flywheel had come to a complete rest. A total breaking time of 5 seconds or less was considered passing criteria, whereas any longer braking period would be considered a failure. The system's braking performance is found below in Table 18.

Table 18. Results for brake time test.

Operating Speed [RPM]	Test #1, *t* [sec]	Test #2, *t* [sec]	Test #3, *t* [sec]
200	9.75	9.61	9.72
100	5.58		
60	3.64		

The original braking system was not implemented as intended, but the motor was able to emulate similar functionality for this test. This is discussed in further detail in Next Steps Chapter 9.3.

8 Project Management

From the beginning, this project has been unique in comparison to others. Instead of being handed a problem to solve, our sponsor, Mr. Bhutani left it up to us as designers to identify a problem and define our own scope. As the project progressed, so did the project goals. We shifted from designing a commercially viable product to designing a proof-of-concept prototype. These factors all culminated in a different project timeline than anticipated, as described in the following sections.

8.1 Project Timeline

The design process and project timeline closely followed Cal Poly's quarter system, with key deliverables within Fall, Winter, and Spring. A Gantt chart, as seen in Appendix U, helped visualize project steps and monitor progress. Additionally, Table 19 catalogs important project milestones and their due dates throughout the whole project.

Table 19. Key project deliverables with dates included.

Deliverables	Description	Due Date
Preliminary Design Review (PDR)	Presented research and concept of final design to date. This set the building blocks of the project.	11/10/20
Critical Design Review (CDR)	Detailed explanation of all information needed to build the final, including manufacturing and testing plans.	2/9/2021
Verification Prototype (VP) Sign-Off	Completion of full Verification Prototype, approval for testing	5/13/2021
Design Verification Plan & Report (DVPR) Sign-Off	Completion of all design verification tests, review of test results and conclusions	5/27/2021
Final Design Review (FDR)	Culmination of all analysis to support final design decisions, discussion of maintenance and safety considerations, and a thorough cost analysis	6/3/2021

The beginning of Fall quarter was spent setting an appropriate and feasible scope based on budget, time, and team experience. After a proper problem definition was developed, we identified four primary energy storage methods and thoroughly researched each to better understand its feasibility. Through matrices and group discussions, the advantages and disadvantages for all methods were compared, yielding a flywheel storage system as the best alternative. With a specific path chosen, extensive brainstorming of conceivable flywheel design configurations began. All ideas went through an elimination and consolidation process until there was one design to move forward with. This idea was presented in our Preliminary Design Review.

To allow more time to generate and evaluate design decisions, our Critical Design Review was pushed back by several weeks during Winter quarter. During this period, we learned to balance between the optimization of the best possible solution and the quick selection of a design to keep the process in motion. This extra time played a vital part in our project's success, but there was a caveat of limited manufacturing and testing time.

Spring quarter marked the beginning of the verification prototype production. Manufacturing extended past the original deadline due to unforeseen circumstances, pushing the VP and DVPR Sign-Off deliverables a couple weeks off schedule. Despite these setbacks, our team was able to keep up with the difficult build and troubleshoot testing problems to finish the construction and verification of the prototype.

8.2 Project Management Reflection and Improvements

Our team did an extremely efficient job at assigning roles and responsibilities to those whose backgrounds, skillsets and schedules aligned the best. This was especially helpful during Spring quarter; with all the COVID restrictions in place for the machine shop, as only two team members could schedule manufacturing time. Divvying up the production of subassemblies and related tasks was key to using the limited time productively.

As mentioned earlier, the exploratory nature of this project led to delayed milestones and deliverables. While the extra time was valuable, it did lull us into a false sense of security. The project would have benefitted from the execution of a few key design decisions over Winter break and ordering parts before spring break to set us up for success during the manufacturing process. Additionally, project planning could have been aided by further utilization of the Gantt chart. As deadlines were pushed back, concurrently updating the Gantt chart instead of waiting until a report was due would have helped the team visualize and think ahead about what to prioritize.

Outsourcing certain manufacturing processes and reaching out to experts for assistance truly improved the quality of the prototype. However, these decisions did introduce their own side effects. As more stakeholders are added to the project, there was greater possibility for error, miscommunications, and time delays. In the future, we need to be more direct with our timeline and expectations.

9 Conclusions

The document is a culmination of the work our team produced in the last nine months. We were able to complete thorough research into four main sustainable energy storage types and focus our design process specifically on the flywheel, which seemed to be the most feasible with a high energy density and lower cost. The team then focused our skills into ideation in order to create a fully functioning flywheel energy storage system. The system was constructed over the course of five weeks in April and May and was subsequently tested in late May. The project has been managed using a Gantt chart, and the costs have been kept under close watch using a project budget sheet.

As our build process was pushed back, we ordered the Verification Prototype components at the beginning of Spring quarter. Once arrived, we built the system and subsequently tested the kinetic flywheel, both of which were completed on time with ample time to wrap up our project. The system will be temporarily stored in the Energy Lab in Engineering 13-205 until a more permanent location can be orchestrated or if our sponsor wishes to have the prototype himself.

The verification prototype was able to achieve the core goals we had initially set out to accomplish. Since our project was a scaled-down prototype of a commercially viable system, the goal was not to optimize the system but rather show that the concept and scaled design were valid. Despite setbacks in the manufacturing process and limitations on operating conditions, the flywheel was able to spin freely and demonstrate the effective storage of an energy source. Even more important than system storage, the sufficient discharge of said energy to an appropriately sized load was achieved, powering an arrangement of LEDs for sustained periods of time. Our flywheel even exceeded the most recent expectations for operating speed, which demonstrated incredibly stable operation through and past our 200 RPM benchmark, unlocking an additional 56% capacity when spun to 250 RPM.

Unfortunately, the system was unable to hit all benchmarks we had initially set out to accomplish. When our system had an operating speed of 5000 RPM, the intended storage capacity was approximately 1.15 kWh, which would be sufficient to fill power generation gaps during daytime operations for a residential house. Once our flywheel operating speed was reduced to 200 RPM, the total energy storage plummeted to 0.16% of the original storage capacity. Similarly, the system was estimated to spin for prolonged periods of time given the high 5000 RPM and low friction bearings. Once the speed was cut and the bearings were received, the results from the power loss test fell substantially short of the expected value. Instead of spinning for a duration of 30 minutes after input power was halted, the system only remained moving for just over 30 seconds.

9.1 Design Modifications During Manufacturing Process

Through the manufacturing process, certain overlooked design details had to be reconciled through modifications to the original plan. These modifications are not reflected in the current CAD files at the request of Professor Schuster, but a comprehensive discussion of these changes is included below.

When the weldment drawing was handed to the shop technician responsible for welding our chassis, the significance of the lower support bars' locating dimensions was not interpreted as planned. The dimensions needed to be precise in order for the lower bearing assembly, and consequently the flywheel subassembly, to be properly located and attached. The communication breakdown resulted in support bars being welded too far apart. However, this error was resolved by welding additional angle iron sections to span the gap and locate the lower bearings. This modification can be seen in Figure 40.

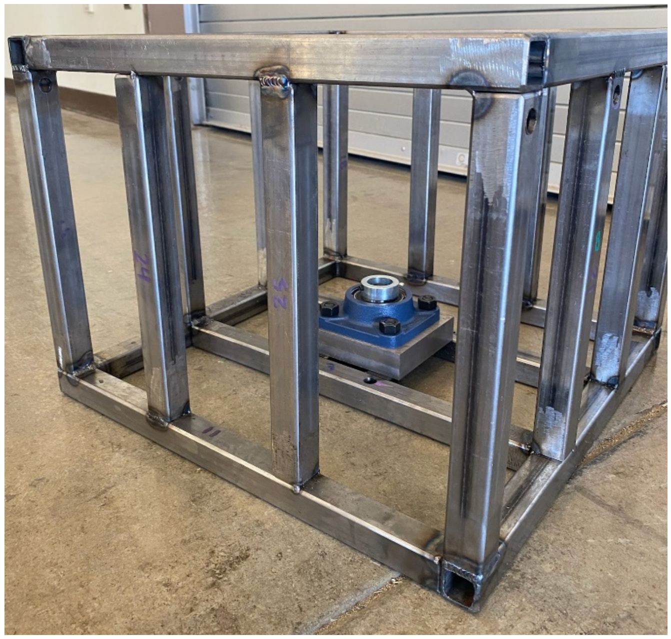

Figure 40. Welded chassis with modified lower bearing assembly.

An oversight in our design process came at the expense of our steel siding pieces. The upper chassis assembly consists of crossbars connected to the frame through a pair of angle irons in order to support the motor and its mounting assembly. Due to the geometric constraints imposed by the dimensions of the frame, this upper chassis assembly could not be lifted up and out of the chassis without a clearance easement. Subsequently, a pair of clearance cut outs were cut on a side plate so that the angle irons could pivot freely and be removed in the event of maintenance or decommissioning, as seen in Figure 41.

Figure 41. Clearance cut outs for upper chassis assembly.

In a similar vein to the previous discovery, the angle iron components were to be mounted to vertical steel tubing using nuts and bolts hidden in the vertical members. Manufacturing constraints and accessibility issues during manufacturing led our team to instead cut through holes on each of the vertical members as well as clearance holes on the exterior siding pieces, as shown in Figure 42. Although this resulted in an exterior that was not as streamlined and elegant as intended, it did simplify the assembly process.

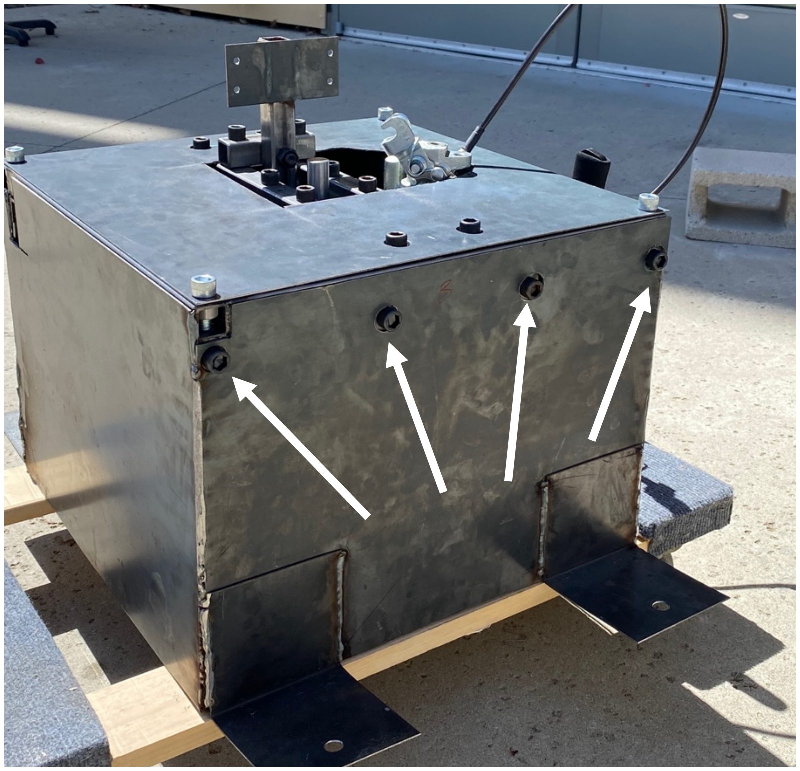

Figure 42. Clearance holes on steel siding.

The most notable system issue came from the braking subassembly. Originally, the subassembly was expected to work and function as any automotive brake would. However, the orientation of the rotor and subsequent effects on the system were critically overlooked. In a car, the rotor and the brake pads are mounted on a vertical face, resulting in little to no frictional effect on the car when unengaged. In the prototype system, the rotor is mounted on a horizontal face, causing the upper brake pad to fall onto the caliper under the effect of gravity. Additionally, automobiles have a much higher torque capacity and rolling resistance from trace braking effects are negligible, neither of which can be said for a kinetic flywheel. Luckily, the motor purchased for our energy storage and generation function had an additional braking feature as part of the software suite. The entire mechanical braking subassembly was removed, and the motor's braking capability was exclusively used to slow the system during testing.

One other issue came from the motor driver safety functions. When the motor driver senses that the motor is not speeding up fast enough, the driver sends an alarm signal and shuts down the motor. This happened many times during testing due to the large flywheel load. There might be a way to turn off this safety feature, but instead we fixed this problem through writing a new program which slowly incremented the desired speed of the flywheel. This greatly reduced the overload alarms.

9.2 Recommendations

Our team has identified several improvements to the project that could have been made given the opportunity. The flywheel's storage potential is restricted by the current radial bearings, which consume a significant portion of the energy stored and limit any prolonged energy storage. We suggest that a magnetic or air-ride bearing system be added to the flywheel to reduce these losses and maximize energy storage. From our Preliminary Design research, we found that these bearings costed several thousand dollars on average and were not off-the-shelf components.

The mixing of unit systems consistently caused issues during both the detailed design process and the manufacturing process. The shaft and brake dimensions were all in metric, but tube lengths were in English, forcing us to constantly convert between unit systems and sometimes drill holes that were not correctly spaced. Future iterations are recommended to streamline the process with strictly metric dimensions. Additionally, common denominations of tube lengths are recommended, as manufacturing vertical members whose lengths must be repeated consistently is difficult if the length is a nonstandard value such as 10.6125” rather than 10.5”.

Since few electronics tools and supplies were available on campus, many of the control pins were connected with jumper wires and breadboards. Although this works temporarily for testing, it is not ideal as jumper wires can easily be removed from the breadboards. We suggest using wire wraps and more solder connections.

Manufacturing a system that simultaneously has an extremely precise subassembly, such as our flywheel subassembly, and a highly variable and imprecise frame like our chassis subassembly presents issues of tolerance. Since welding is an imperfect science with tolerances orders of magnitude larger than that of the bearings, reconciling that difference was difficult. If attempted again, we suggest that the structural members be precision machined, particularly for the hole mounting locations to eliminate any guesswork. If this is unachievable, a more reasonable goal may be designing the mounting interfaces with more variability and customization to allow for minor adjustments in the assembly process.

Aside from system improvements, we have additional Senior Project suggestions that incorporate our project. The flywheel assembly was machined to the best of our abilities, attempting to keep the flywheel as centered and balanced as possible. Despite our intentions, the system is still imbalanced, which presents the following options:

- Re-machine and balance the flywheel assembly to operate safely with resonant frequencies well above the maximum operating limits.
- Implement the flywheel system in the Vibrations Lab curriculum as a scaled demonstration tool for future ME318/517/518 students.
- Construct a dynamic vibration deadening system that would cancel out the mass imbalance of our flywheel system.

Through our analysis of friction, windage losses are a significant contributor to flywheel performance. We envision that a future project group could tackle the challenge of building a vacuum chamber for operation and/or incorporating magnetic bearings to optimize frictional losses. This additional measure could identify empirical results and compare those to the theoretical results outlined in Appendix G.

9.3 Next Steps

The system has a few necessary upgrades in order to continue prolonged use beyond the Spring 2021 quarter. Firstly, the current arrangement of attachment points that interface with the T-slot tracks found in the Structures and Composites Lab are slightly misaligned. As a result, only three of the four holes designed to secure the system can be mounted. A new hole would need to be redrilled in one of the 90˚ bends to enable flexibility in mounting and ensure a solid connection during operation.

Testing of the prototype uncovered an additional margin of improvement for safe operating speeds, as the flywheel was able to spin past our initial 200 RPM limit without any excessive vibrations. In the event of expanding energy storage, the system's motor and associated drivers must be upgraded to spin at a higher RPM range, which would change the internal gearing of the motor and increase the output amperage.

The system is intended to be external to a residential home or housing complex, but the current prototype is not built for such conditions. As it is a proof-of-concept, the verification prototype must be weatherized with a protective coating to stave off any potential rust from long-term environmental exposure. We recommend additional preventative measures such as storing the flywheel assembly in a climate-controlled facility if possible.

As discussed previously, testing uncovered the inherent design flaws in using automotive brake components in a low friction application such as our system. Although the motor was able to accomplish the braking function and the caliper assembly was removed, any future user must seriously consider an alternative braking system before extensive use. A suitable replacement would most likely come from industry applications that necessitate a low friction assembly. Our team suggests researching into the work collegiate teams like Cal Poly Supermileage use for their braking systems.

Finally, for any general transportation of the flywheel system, we would recommend moving the assembly in a well-secured storage compartment that would inhibit any shifting or tipping. Although the full system is over 150 pounds, it tends to move in transport if not isolated.

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Appendix A. QFD

Correlations	
Positive	+
Negative	–
No Correlation	

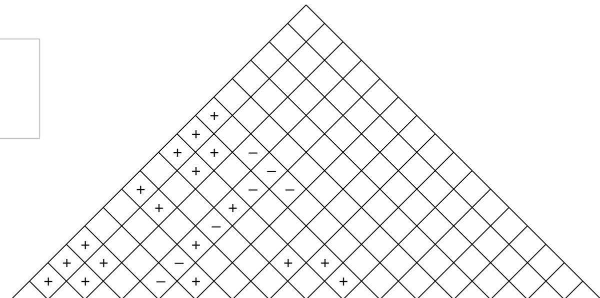
Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

QFD House of Quality

Project: F51 Sustainble Energy Storage

Revision Date: 10/7/20



		WHO: Customers					Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	NOW: Curr. Products					
							Direction of Improvement	▲	▲	▼	▼	▼	▼	▼	▼	▲	▼	▲											
Row #	Weight Chart	Relative Weight	Off Grid Customers	Manufacturers	Residential Homeowners	Maximum Relationship	HOW: Engineering Specifications (Tests) / WHAT: Customer Requirements (Needs/Wants)	Maximum Power output	Sustained power output	Noise Measurement	Market Cost	Volume	Weight	Manufacturing Cost	Power Loss test	Storing Capacity	Charge Time	Group apperance rating						Our Current Product	Competitor #1: *Velkess Flywhee*	Competitor #2: *CCT Thermal Ba*	Competitor #3: *Capacitor Bank*	Competitor #4: *Enphase Ensem*	Row #
1		10%	10	3	10	9	Stores sufficient energy usage	●	●		○	○	○	○	●	●	●								5	5	3	5	1
2		6%	4	2	8	9	Compact form factor	○	○		▽	●	▽	○		●	▽	○							4	1	5	5	2
3		8%	8	1	9	9	Quiet	▽	▽	●				▽	○	▽									2	2	4	3	3
4		12%	9	7	9	9	Cost efficient	▽	▽	○	●	○	○	●	▽	○	○								2	2	1	3	4
5		15%	10	10	10	3	Safe operation	○	○				○	▽											2	4	3	5	5
6		11%	8	8	6	3	Low maintenance	▽	▽		○			▽			▽								4	4	3	4	6
7		12%	9	7	9	9	Sustainably sourced materials (Non-toxic)				●			●											5	3	2	0	7
8		6%	6	1	6	9	Low energy loss	●	●	▽	○	▽			●	○	●								3	4	3	4	8
9		6%	5	1	7	9	Conveniently controlled by user										○	●							3	4	4	5	9
10		8%	5	5	7	9	High energy density to weight ratio	▽	▽		●	●	●	○		○		▽							2	2	5	5	10
11		7%	1	10	1	9	Manufacturability	▽	▽		●	○		●											2	4	3	3	11
12		0%																											12
13		0%																											13
14		0%																											14
15		0%																											15
16		0%																											16

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	HOW MUCH: Target Values	1 kW	0.5 kW	30 dB	$5,000	1 m^3	750 lb max	$2,500	5% per 8 hours	3.5 kWh	8 hrs	>70% :)					
	Max Relationship	9	9	9	9	9	9	9	9	9	9	9					
	Technical Importance Rating	252.4	252.4	111.8	436.2	222.2	189.5	383.7	179.7	234.1	214.2	77.89	0	0	0	0	0
	Relative Weight	10%	10%	4%	17%	9%	7%	15%	7%	9%	8%	3%	0%	0%	0%	0%	0%
Curr. Products	Our Current Product																
	Competitor #1: Velkess Flywheel	5	5	3	1	4	3	1	2	5	5	5					
	Competitor #2: CCT Thermal Battery	4	4	2	1	0	1	2	4	5	4	2					
	Competitor #3: Capacitor Bank	5	2	4	2	4	4	1	2	3	5	2					
	Competitor #4: Enphase Ensemble	5	5	4	0	3	4	1	4	5	5	5					
	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Appendix B. Jamboard Brainstorming

Accepts Energy

CVT: continuous variable transmission for maintaining our rpm we need

From a car/motorcycle/bicycle ? <-- Comes down to torques

Use charge controller to manage where power is going

House/Flywheel depending on what needs power

What is the max # of solar panels we want to allow to be connected?

Flywheel Papers / Patents

http://www.asee-se.org/proceedings/ASEE2014/Papers2014/26.pdf

https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.598.8816&rep=rep1&type=pdf

Allow for multiple inputs

be that solar/hydro/wind

Stores Energy

spins fast enough to supply enough power

Is there a baseline rpm that we need to consider as "0% charge"?

Needs very little to no maintenance to keep storing energy for years

What is being used to overcome frictional losses? Is it the energy itself or an external motor delivering bursts?

Energy has very little losses while being stored

To maintain, should a compressor function be added to maintain vacuum in the unit?

Where would this energy input come from?

Possible to create a vacuum and seal it, that way don't have to have a separate system set up?

Delivers Power

Assuming flywheel questions:

Do we need another storage device for steady output?

Possible to connect supercaps as aux systems to steady output? Nick says we only need one

How do we regulate the output?

How do we get energy out of it?

feedback loop to adjust how much power we need.

convert variable frequency AC to DC and then back to 60 Hz AC

Keep "transmission" and motor inside housing

How to regulate that power

will the power pull just take the amount it needs and slow the system down?

use computer smarts to slow down the exact amount for amount of power needed?

button controls on system itself

RF

Completely wired to computer

wifi enabled/bluetooth control from computer

SSH: virtual computer lab type thing

app with graphs/data

Manages system control

arduino computer inside to record data

wifi/bluetooth chip

real time data

History data

Appendix C. Pugh Matrices

Sustainable Materials:

	High strength steel	CFRP	GFRP	High strength aluminum alloy	Ti Alloys	Cast Iron
Sustainably sourced & produced	D	S	S	S	S	S
Manufacturability	A	-	-	S	-	-
Cost efficient	T	-	-	-	-	+
High energy density to weight ratio	U	+	+	S	-	-
Durability	M	+	+	S	-	-
Total:		0	0	-1	-4	-2

Operates Safely:

	Truck Brake	Flywheel Levers	Linear Actuator	Axle Contraction	Axle Actuator	Sand Pit
Safe operation	D	-	S	S	S	-
Manufacturability	A	-	S	-	S	S
Cost efficient	T	S	-	-	-	+
Conveniently controlled by user	U	S	S	S	S	S
Total	M	-2	-1	-2	-1	0

Manages System Control:

	Button Control	Wired to Computer	RF	Bluetooth	WiFi
conveniently controlled by user	D	--	+	+	++
cost efficient	A	+	S	S	S
compact form factor	T	-	S	+	+
manufacturability	U	+	+	-	-
low maintenance	M	-	-	S	S
safe operation		S	S	+	+
Totals		-2	1	2	3

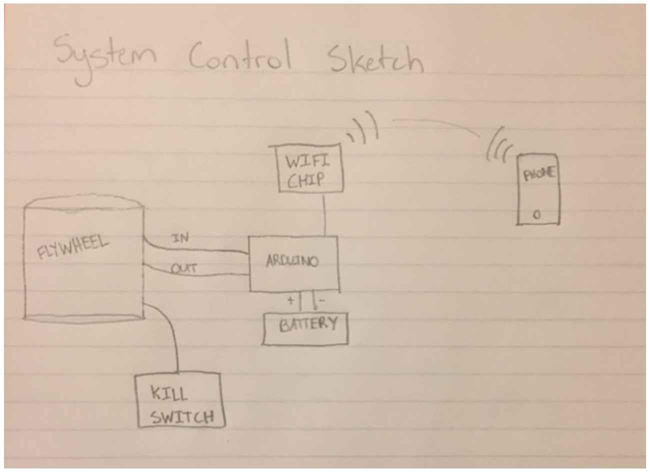
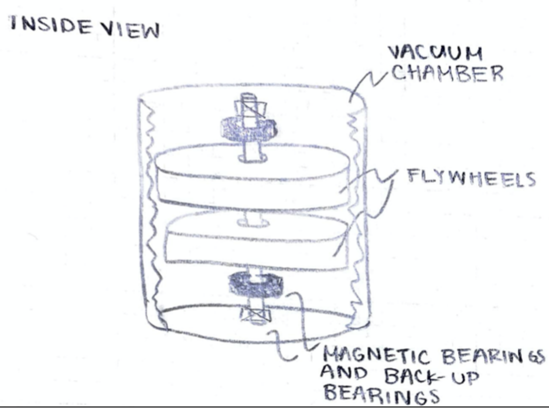
Delivers/Accepts Electric Power:

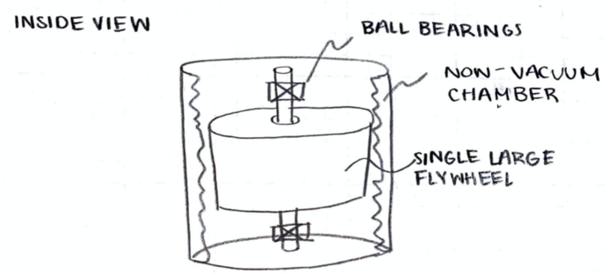
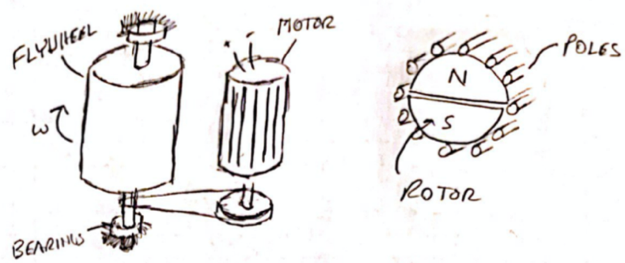
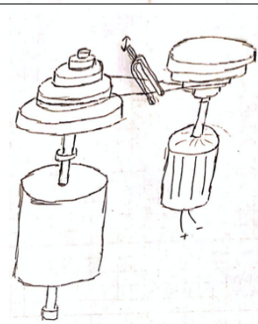
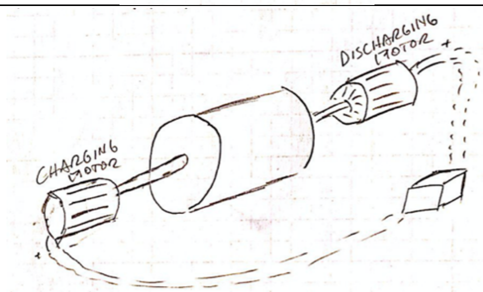
	car transmission	Variable freq system	CVT transmission	power regulating system (aux supercaps)	clutch system	grounded excess system	excess feedback loop
compact form factor	D	+	+	+	S	+	+
quiet		+	+	+	-	+	+
safe operation	A	+	S	-	-	+	+
low maintenance		+	+	+	-	-	-
Conveniently controlled by user	T	S	S	S	S	S	S
cost efficient		+	+	S	S	S	+
Energy Efficient	U	S	S	S	-	-	S
manufacturibility		+	+	+	S	+	+
Totals	M	6	5	3	-4	2	4

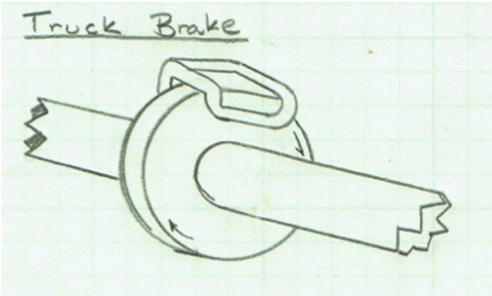
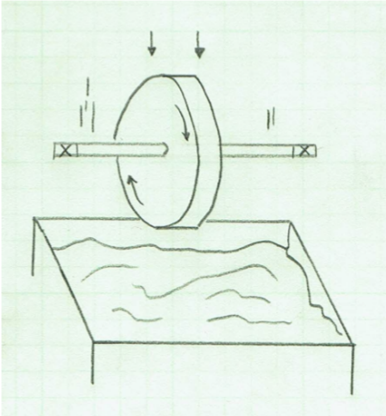
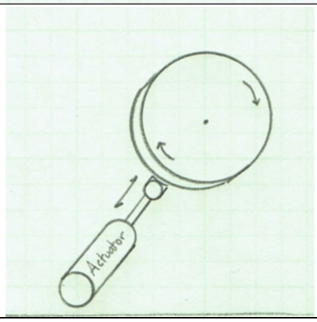
Stores Energy:

	Ball Bearings	Roller Bearings	Magnetic Bearings with Backup Bearings	Multiple Flywheels	One Large Flywheel	Non-Vacuum-Sealed Chamber	Vacuum Sealed Chamber	Different Gas within Chamber
Sustainably soured materials (non-toxic)	D	S	S	D	S	D	S	S
Low energy loss		S	+		S		+	S
Cost Efficient	A	S	-	A	S	A	S	-
Stores sufficient energy usage		N/A	N/A		S		N/A	N/A
Safe operation	T	S	S	T	-	T	S	S
Low maintenance		S	-		+		-	-
Manufacturability	U	S	-	U	+	U	-	-
High energy density to weight ratio		N/A	N/A		S		N/A	N/A
Quiet	M	S	S	M	+	M	+	S
Total:		0	-2		2		0	-2

Appendix D. Morphological Matrix

Concept	Picture	Description
WIFI Capable		The top choice for managing system control is over WIFI. This allows more convenience for the user and allows them to not be at the actual location to control the energy storage. This will make it more of a smart home device. Combined with this system, we will use an Arduino board for processing control commands and recording data. Button control, at least for shutting off the power, is an important safety feature that we will add to the system. It will also allow for manual control when it is more convenient for the user to not use Wi-Fi___33 to control it. The other options are similar to Wi-Fi___33 control expect allow for less range and are less reliable.
Vacuum Chamber, Magnetic Bearings, Multiple Flywheels		The vacuum chamber will decrease losses due to friction and create a lower energy loss system. The magnetic bearings have a long life, reducing the maintenance required by the consumer.

<table>
<tr><td>Non-Vacuum Chamber, Ball Bearings, One Large Flywheel</td><td>
</td><td>A non-vacuum chamber is easier to manufacture, maintain, and is less expensive. A single, larger flywheel might be quieter(?). Ball Bearings will be easier to manufacture.</td></tr>
<tr><td>Variable Frequency System</td><td>
</td><td>This system works by both changing the output frequency and number of poles of the rotor to output correct power. Will have 2 step inverters, (AC variable to DC to AC 60Hz). Changing number of poles is effectively same as changing gears.</td></tr>
<tr><td>Continuously Variable Transmission</td><td></td><td>Doesn’t change gears in normal sense, varies belt to change gear ratio instead. This is done by pushing belt in and further out depending on situation.</td></tr>
<tr><td>Excess Feedback Loop</td><td>
</td><td>Always producing at some level. Any excess that house is not using gets sent back to charge up again.</td></tr>
</table>

Truck Brake		Truck Brake is an effective off-the-shelf product that can be used to slow the flywheel in the event of an issue or error
The Sand Pit		The sand pit, which would release the flywheel and drop it into a pit of sand or friction material to bring the disk to a halt quickly
Linear Actuator		Linear actuators would apply braking material to either the rotor or shaft of the flywheel

Appendix E. Energy Storage Hand Calculations

FSI - SUSTAINABLE ENERGY STORAGE | CALCULATIONS | 3/9/21

STORAGE CAPACITY

GIVENS:

$$\omega_{operating} = 200 \text{ rpm}$$
$$\rho_{aluminum} = 2700 \text{ kg/m}^3$$
$$I_{rotor} = 0.0494 \text{ kg m}^2$$
$$D_{flywheel} = 355.6 \text{ mm}$$
$$H_{flywheel} = 76.2 \text{ mm}$$
$$\text{Bolt } D = 12 \text{ mm}$$
$$L_{Bolt} = 60 \text{ mm}$$

FIND: Total Energy Stored

$$KE = \Sigma \tfrac{1}{2} I \omega^2$$
$$= \tfrac{1}{2}(I_{flywheel} + I_{brake})\,\omega^2$$
$$= \tfrac{1}{2}\left(\tfrac{1}{2}\rho \cdot \pi \cdot \tfrac{D^2}{4} \cdot H \cdot \tfrac{D^2}{4} + I_{brake}\right)\omega^2$$
$$= \tfrac{1}{2}\left[\tfrac{1}{2}\left(\tfrac{1}{4^2}\right)\left(2700 \tfrac{kg}{m^3}\right)(\pi)(0.3556\,m)^4(0.0762\,m) + 0.0494 \text{ kg m}^2\right]\left(200 \tfrac{rev}{min} \cdot \tfrac{1\,m}{60\,s} \cdot \tfrac{2\pi}{1\,rev}\right)^2$$

$$KE = 81.688 \text{ W/s} = \boxed{81.688 \text{ J}}$$

Appendix F. Design Hazard Checklist

Y	N	
X		1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
X		2. Can any part of the design undergo high accelerations/decelerations?
X		3. Will the system have any large moving masses or large forces?
	X	4. Will the system produce a projectile?
	X	5. Would it be possible for the system to fall under gravity creating injury?
	X	6. Will a user be exposed to overhanging weights as part of the design?
	X	7. Will the system have any sharp edges?
	X	8. Will any part of the electrical systems not be grounded?
X		9. Will there be any large batteries or electrical voltage in the system above 40 V?
X		10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
	X	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
	X	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
	X	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	X	14. Can the system generate high levels of noise?
X		15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
	X	16. Is it possible for the system to be used in an unsafe manner?
	X	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
Flywheel drum spins at a high rate of speed within the system	Flywheel will be contained in vacuum sealed steel case, and a truck brake will be included for any necessary emergency shut-off of the system to slow down the spinning drum.	2/1/21	
Flywheel will be accelerated and decelerated during the charging and discharging cycles, depending on the power demand from the user.	Transmission will be included to change speed to ensure the flywheel is sped up and sped down in a safe manner. A truck brake, mentioned previously, can be applied to the drum in order to slow the spin or stop it completely.	2/1/21	
Flywheel must have a high inertial mass in order to store enough energy for the system.	Flywheel will be encased in a protective chamber, as mentioned before, and during the design process, we will make sure to not go overboard with the size compared to the power output we are intending to reach.	2/1/21	
The system is expected to generate a voltage of 120 V with varying amperage in order to meet the load demands created by the house.	All wiring and connections will be insulated. Components and wires will be rated to withstand the correct power. Fuses will be added for over current protection.	1/26/21	
The main purpose of this project is to create an energy storage system, so our flywheel design will definitely have stored energy.	Emergency stop system will be included; truck brake can be engaged to stop the spinning drum. Also, user control will have the ability to fully shut-off the system as well.	1/23/21	
The system will be outside adjacent to a building and will be open to all the elements.	All components of the system will be inside a containment unit, protected against environmental conditions.	2/5/21	

Appendix G. Hand Calculations for System Energy Losses (Windage and Bearing).

$L = 3\,in = 0.0762\,m$

$R = 7\,in = 0.1778\,m$

$\omega = 200\,rpm \times \frac{min}{60\,s} \times \frac{2\pi\,rad}{1\,rev}$

$\longrightarrow \omega = 20.94\,rad/s$

Air @ STP

$\rho = 1.225\,kg/m^3$

$\mu = 1.789e{-5}\,\frac{kg}{m \cdot s}$

$$Re = \frac{\rho \overset{\omega R}{V} L}{\mu} \leftarrow 2\pi R$$

$$= \frac{(1.225\,\frac{kg}{m^3})(20.94\,\frac{rad}{s})(0.1778\,m)(2\pi)(0.1778\,m)}{1.789e{-5}\,\frac{kg}{m \cdot s}}$$

$Re = 5.095$

$\therefore$ Laminar

$$P_{W_i} = \left[1.328\,\rho_g L \pi R^4 \left(\frac{\overset{1.46e{-5}\,m^2/s}{\nu}}{2\pi R^2}\right)^{1/2}\right] \omega^{2.5}$$

$$= 1.328(1.225\,\frac{kg}{m^3})(0.0762\,m)\pi(0.1778\,m)^4 \times \cdots$$

$$\times \left(\frac{1.46e{-5}\,m^2/s}{2\pi(0.1778\,m)^2}\right)^{1/2}(20.94)^{2.5}$$

$P_{W_i} = 6.7\,mW$

SKF FRICTION | RADIAL BEARING | 1

$M = M_{rr} + M_{sl} + M_{seal} + M_{drag}$

M_{rr}: $M_{rr} = \phi_{ish}\,\phi_{rs}\,G_{rr}(\nu n)^{.6}$

$$\phi_{ish} = \frac{1}{1+1.84\cdot10^{-9}(n d_m)^{1.28}\cdot\nu^{.64}}$$

ASSUME GREASE W/ LITHIUM THICKNER

$\rightarrow \nu = 70\ mm^2/s$

d_m = MEAN DIA = 38.1 mm (1.5 in)

$$\phi_{ish} = \frac{1}{1+1.84\cdot10^{-9}(200\cdot 38.1\,mm)^{1.28}(70\,mm^2/s)^{.64}}$$

$\phi_{ish} = .997$

$$\phi_{rs} = \frac{1}{e^{\left[K_{rs}\nu n(d+D)\sqrt{\frac{K_Z}{2(D-d)}}\right]}}$$

$K_{rs} = 6\times10^{-8}$ ← GREASE, $K_Z = 4.8$ (SELF ALIGNING BALL BEARING) | $D = 44.5\,mm$, $d = 25.4\,mm$

$$\phi_{rs} = e^{-\left[(6\times10^{-8})(70\,mm^2/s)(200)(44.5+25.4\,mm)\sqrt{4.8/2(44.5+25.4)}\right]}$$

$\phi_{rs} = .989$

$G_{rr} = R_1\, d_m^{1.97}\left[F_r + F_g + R_2 F_a\right]^{.54}$, $F_g = R_3\, d_m^{4}\, n^2$

(ASSUME 10N RADIAL LOAD)

$$= (3.1\times10^{-7})(38.1)^{1.97}\left[(10\,N) + (3\times10^{-12})(38.1)^4(200)^2 + 0\right]^{.54}$$

$G_{rr} = .0041$

Scanned with CamScanner

$M_{rr} = (.997)(.989)(.0041)(70 \cdot 200)^{.6}$

$M_{rr} = 1.243 \ Nmm = \underline{.00124 \ N \cdot mm}$

NOW FOR M_{SL}

$M_{SL} = G_{SL} \mu_{SL}$

$G_{SL} = S_1 d_m^{-.12}\left[(F_r + F_g)^{4/3} + S_2 \cancel{F_a^{4/3}}^{\,0}\right]$, $F_g = S_3 d_m^{3.5} n^2$

$= 4.5 \cdot 10^{-3} (38.1)^{-.12}\left[(10 + 3 \cdot 10^{-12} \cdot (38.1)^{3.5} \cdot (200)^2)^{4/3}\right]$

$G_{SL} = \underline{.0630}$

$\mu_{SL} = \phi_{bL} \mu_{bL} + (1 + \phi_{bL}) \mu_{EHL}$

$\phi_{bL} = \dfrac{1}{e^{2.6 \cdot 10^{-8}(n\nu)^{1.4} d_m}} = \dfrac{1}{e^{2.6 \cdot 10^{-8}(200 \cdot 70)^{1.4}(38.1)}} = .5317$

$\mu_{bL} = .12$

$\mu_{EHL} = .04$

$\mu_{SL} = (0.5317)(.12) + (1 + .53)(.04) = \underline{.125}$

$M_{SL} = (.0630)(.125) = \underline{.008 \ Nmm}$

$M_{SEAL} = K_{S1}\, d_s^{\beta} + K_{S2}$

$\beta = 2,\ K_{S1} = .014,\ K_{S2} = 10,\ d_1 = 33.74\,mm$

$M_{SEAL} = (.014)(33.74\,mm)^2 + 10 = \underline{25.94\ Nmm}$

$M_{drag} = .4\, V_m\, K_{ball}\, d_m^5\, n^2 + 1.093\times10^{-7} n^2 d_m^3 \left(\frac{n d_m^2 f_t}{\nu}\right)^{-1.379} R_s$

$V_m = .0012$

$K_{ball} = \frac{i_{rw} K_Z (d+D)}{D-d} 10^{-12} = \frac{(1)(4.8)(44.5+25.4)}{(44.5-25.4)} \times 10^{-12} = 1.756\times10^{-11}$

$f_t = 1$

FIRST NEED t

ASSUME FULLY SUBMERGED ($H = d_m$)

$t = 2\cos^{-1}\left(\frac{.6 d_m - H}{.6 d_m}\right) = \underline{4.6\ rad}$

$R_s = .36\, d_m^2 (t - \sin t) f_A, \quad f_A = .05\, \frac{K_Z(d+D)}{D-d}$

$= .36\,(38.1^2)(4.6 - \sin 4.6)\,.05\, \frac{(4.8)(44.5+25.4)}{44.5-25.4}$

$R_s = 2567.4$

$M_{drag} = .4(.0012)(1.756\times10^{-11})(38.1)^5(200)^2 + 1.093\times10^{-7}(200)^2 \cdot (38.1)^3 \left(\frac{200\cdot 38.1^2 (1)}{70}\right)^{-1.379} (2567.4)$

$\underline{M_{drag} = 6.368\ N\cdot mm}$

$M = M_{rr} + M_{SL} + M_{SEAL} + M_{drag}$

$= (.00124\ Nmm) + (.008\ Nmm) + (25.94\ Nmm) + (6.368\ Nmm)$

$M = 32.32\ Nmm$ OR $\boxed{0.032\ N\text{-}m}$

THRUST BEARING FRICTION CALCS

$d = 5/8"$, $D = 1\ 1/8"$ $\Rightarrow d_m = .5(d+D) = .875"$

$= .625"$ $= 1.125$ $= 22.25\ mm$

$= 15.88\ mm$ $\approx 28.58\ mm$

$M = M_{rr} + M_{sl} + \cancel{M_{seal}}^{0} + M_{drag}$

$M_{rr} = \phi_{ish}\phi_{rs}G_{rr}(\nu n)^{0.6}$, ASSUME AGAIN $\nu = 70\ mm^2/s$

$$\phi_{ish} = \frac{1}{1 + 1.84\times10^{-9}(n d_m)^{1.28}\nu^{.64}}$$

$$= \frac{1}{1 + 1.84\times10^{-9}(200\ rpm \cdot 22.25)^{1.28}(70)^{.64}}$$

$\phi_{ish} = .997$

$$\phi_{rs} = \frac{1}{e^{\left[K_{rs}\nu n(d+D)\sqrt{K_Z/2(D-d)}\right]}}, \quad K_Z = 4.4 \text{ (THRUST)}$$

$$= e^{-\left[6\times10^{-8}\cdot(70\ mm^2/s)(200\ rpm)(15.88+28.58)\sqrt{4.4/2(28.58-15.88)}\right]}$$

$\phi_{rs} = .985$

$G_{rr} = R_1 d_m^{2.38} F_a^{.31}$, $R_1 = 2.25\times10^{-6}$, $F_a = 300\ N$

$$= (2.25\times10^{-6})(22.25)^{2.38}(300)^{.31}$$

$G_{rr} = .0212$

2

$$M_{rr} = (.997)(.985)(.0212)(70 \cdot 200)^{.6}$$

$$M_{rr} = 6.40 \ \text{Nmm} = \underline{.0064 \ \text{N}\cdot\text{m}}$$

$$M_{sl} = G_{sl} \mu_{sl}$$

$$G_{SL} = S_1 d_m^{.62} F_a \quad , \ S_1 = .154$$

$$= (.154)(22.25)^{.62}(300)$$

$$\underline{G_{SL} = 316.215}$$

$$\mu_{SL} = \phi_{bL} \mu_{bL} + (1 - \phi_{bL}) \mu_{EHL}$$

FROM PLOT $\phi_{bL} \approx 0$

$$\mu_{EHL} = .04$$

$$\mu_{SL} = .04$$

$$M_{SL} = (316.218)(.04) = \underline{12.648 \ \text{N}\cdot\text{mm}}$$

$$M_{drag} = 4 V_M K_{roll} C_w B d_m^4 n^2 + 1.093 \times 10^{-7} n^2 d_m^3 \left(\frac{n d_m^2 f_t}{2}\right)^{-1.379} R_s$$

$$\underline{V_M = .0008} \quad , \quad H/d_m = {}^{1.984}/_{22.25} = .089$$

5/64

$$K_{roll} = \frac{K_L K_Z (d + D)}{D - d} \times 10^{-12} \quad , \ K_L = .43$$

$$K_{roll} = \frac{(.43)(4.4)(15.88 + 28.58)}{(15.88 + 28.58)} \times 10^{-12} = \underline{6.6 \times 10^{-12}}$$

3

$$C_w = 2.789\times10^{-10}\cdot I_d^3 - 2.786\times10^{-4} I_D^2 + .0195 I_D + .6439$$

$$I_d = 5\,\frac{K_L B}{d_m}$$

$$= 5\,\frac{(.43)(1.984)}{22.25} = \underline{.1917}$$

$$C_w = 2.789\times10^{-10}(.1917)^3 - 2.786\times10^{-4}(.1917)^2 + .0195(.1917) + .6439$$

$$\underline{C_w = .6476}$$

$$\underline{f_t = 1}$$

$$R_s = .36\cdot d_m^2(t - \sin t)\,f_A$$

$$f_A = .05\,\frac{k_2(D+d)}{(D-d)}$$

$$= .05\,\frac{(4.4)(28.58+15.88)}{(28.58-15.88)} = \underline{.7702}$$

$$t = 2\cos^{-1}\left(\frac{.6d_m - H}{.6d_m}\right)$$

$$= 2\cos^{-1}\left(\frac{.6(22.25)-1.98}{.6(22.25)}\right) = 63.209$$

$$R_s = .36\cdot(22.25)^2(63.209 - \sin(63.209))(.7702)$$

$$\underline{R_s = 8553.98}$$

$$M_{drag} = 4(.0008)(6.6\times10^{-12})(.647)(1.98)(22.25)^4(200)^2$$

$$+ 1.093\times10^{-7}(200)^2(22.25)^3\left(\frac{200\cdot22.25^2(1)}{70}\right)^{-1.379}(8553.96)$$

$$M_{drag} = 2.65\times10^{-4} + 18.628 = 18.629 \ Nmm$$

$$M = M_{rr} + M_{sl} + M_{drag}$$

$$= (6.40) + (12.645) + (18.63)$$

$$M = 37.677 \ N\cdot mm = \boxed{0.0377 \ Nm}$$

FOR TOTAL DRAG

$$M = M_{BEARING} + M_{THRUST} + M_{DRAG}$$

$$= (.032\ N\cdot m)\cdot 2 + (.037\ N\cdot m) + \left(\frac{6.7\,mW}{20.94\,rad/s}\right)\cdot\left(\frac{1\,W}{1000\,mW}\right)$$

$$\boxed{M = .0699\ Nm}$$

THE TORQUE FROM FRICTION TO OVERCOME @ 2000 RPM

TIME TO STOP FROM LOSSES ON FLYWHEEL

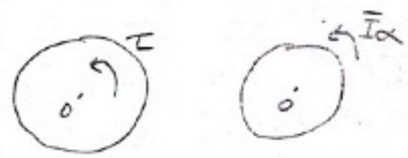
TOTAL TORQUE AT OPERATING SPEED IS...

$$\tau = 0.069 \text{ N-m}$$

ASSUME THIS IS TORQUE AT ALL ROTATING SPEEDS, THIS IS CONSERVATIVE ASSUMPTION AS THE FRICTION TORQUE SHOULD DROP AS IT SLOWS, BUT WILL SUFFICE ☺

FIND ACCELERATION...

FBD MAD



$$\Sigma M_o = \Sigma \bar{I}\alpha_o$$

$$\tau = \bar{I}\alpha$$

$$\alpha = \tau / \bar{I}$$

$$\alpha = \frac{(0.069 \text{ N}\cdot\text{m})}{0.349 \text{ kg}\cdot\text{m}^2}$$

$$\alpha = 0.198 \text{ rad/s}^2$$

USE $\bar{I}$ FROM SOLIDWORKS ASSEM.

$$\bar{I} = 3.494 \times 10^8 \text{ g}\cdot\text{mm}^2$$
$$= 0.349 \text{ kg}\cdot\text{m}^2$$

THEN USING SIMPLE KINEMATIC EQUATION.

$$\omega = \cancel{\omega_0}^{\,0} + \alpha t$$

$$\frac{2\pi \text{ rad}}{1 \text{ rot}} \cdot \frac{1 \text{ min}}{60 \text{ s}} \cdot 200 \text{ RPM} = (0.198 \text{ rad/s}^2)\, t$$

$$20.944 \text{ rad/s} = (0.198 \text{ rad/s}^2)\, t$$

$$\boxed{t = 105.93 \text{ s}}$$

CAN HOLD CHARGE FOR ALMOST 2 MINUTES

Appendix H. Hoop stress calculations for flywheel.

Hoop Stress Calculations for Flywheel

$$\sigma_{\theta\theta}(0) = \frac{3+\nu}{8}\rho\omega^2 b^2$$

$b = 7 \text{ in} = 0.1778 \text{ m}$
$\rho = 2700 \text{ kg/m}^3$
$\nu = 0.33$
$\omega = 200 \text{ rpm} = 20.9 \text{ rad/s}$

$$\sigma_{\theta\theta}(0) = \frac{3+0.33}{8}\left(2700\ \frac{\text{kg}}{\text{m}^3}\right)\left(20.9\ \frac{\text{rad}}{\text{s}}\right)^2 (0.1778 \text{ m})^2$$

$\sigma_{\theta\theta}(0) = 15.5 \text{ KPa}$

Appendix I. Hand Calculations for Fatigue Analysis of Flywheel

1

FATIGUE ANALYSIS AND CYCLE LIFE - FLYWHEEL

ASSUME: $S_{UT} = 45$ ksi, $\rho = 2780$ kg/m³

FIRST FIND Se'

APPROX Se' TO BE HALF OF ULTIMATE STRENGTH

↳ $Se' = 22.5$ ksi

AND NEED TO GO THROUGH ALL K'S

$$Se = Se' \, K_a K_b K_c K_d K_e K_f$$

K_a:

$K_a = a S_{ut}^{\,b}$, $a = 14.4$, $b = -.718$

$K_a = (14.4)(45 \text{ ksi})^{-.718} = \underline{.936}$

K_b: $\underline{K_b = 1}$

K_c: APPROX AS AXIAL ⇒ $\underline{K_c = .85}$

K_d: NO TEMP EFFECTS ⇒ $\underline{K_d = 1}$

K_e: $K_e = 1.0 - .08 z_a$ (FOR 99% RELIABILITY)

$\underline{K_e = .814}$

$\underline{K_f = 1}$

SO...

$Se = Se'(.936)(1)(.85)(1)(.814)$

$\underline{Se = 14.571}$ ksi

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HOW CAN USE EQ FOR FATIGUE STRENGTH

$$S_f = a N^b, \quad a = \left(\frac{f S_{UT}}{S_e}\right)^2, \quad b = -\frac{1}{3}\log\left(\frac{f S_{UT}}{S_e}\right)$$

FROM FIG 6-18 → @ $S_{UT} = 45$ ksi, APPROX $f = 1$

$$a = \left(\frac{1(45 \text{ ksi})}{14.571}\right)^2 = 9.537$$

$$b = -\frac{1}{3}\log\left(\frac{45}{14.571}\right) = -.1632$$

SO... @ 1000 REV

$$S_f = (9.537)(1000)^{-.1632} = \boxed{3.089 \text{ ksi}}$$

$$= \boxed{21.28 \text{ MPa}}$$

Appendix J. Hand Calculations for Buckling of Shaft

DESIGN FOR SECTION A OF SHAFT

ASSUME LENGTH = 8 in, DIA = 1 in
= (.2032 m) = (.0254 m)

FOR STEEL (ALLOY)

$E = 205\ GPa,\ S_y = 585\ MPa$

(ENGINEERING TOOLBOX)

LOAD CASE (STATIC)

ρ OF ALUMINUM · VOLUME = MASS

$m_{ALUM} = (2780\ kg/m^3)\left(\pi \left(\frac{14 in \cdot .0254}{2}\right)^2 (3 in \cdot \frac{.0254 m}{1 in})\right)$

$M_{ALUM} = 21.038\ kg$

FOR AXIAL STRESS

$$\sigma = \frac{F}{A} = \frac{(21.038\ kg)(9.81\ m/s^2)}{\pi\left(\frac{.0254 m}{2}\right)^2} = 407309\ Pa$$

(WELL BELOW)

TRY BUCKLING... FIX-FIX ⇒ C = 1.2

$$(L/K)_1 = \left(\frac{2\pi^2 CE}{S_y}\right)^{1/2} = \left(\frac{2\pi^2(1.2)(205\ GPa)}{585\ MPa}\right)^{1/2}$$

$$(L/K_1)_1 = 91.1$$

FOR OUR ACTUAL...

$$(L/K) = \frac{L}{\sqrt{I/A}} = \frac{.2032\ m}{\sqrt{\frac{\pi/4(.0254/2)^4}{\pi(.0254/2)^2}}} = \frac{.2032}{.00635} = 32$$

SINCE $(L/K) < (L/K_1)$ NEED TO USE JOHNSON BUCKLING

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JOHNSON –

$$P_{CR} = A\left(S_y - b(L/k)^2\right), \quad b = \left(\frac{S_y}{2\pi}\right)^2 \frac{1}{CE}$$

FIRST FIND b –

$$b = \left(\frac{585\,\text{MPa}}{2\pi}\right)^2 \frac{1}{(1.2)\,205\times10^9} = 35238.45$$

SO –

$$P_{CR} = \left(\pi\left(\frac{.0254\,m}{2}\right)^2\right)\left(585\times10^6 - (35238.45)(32)^2\right)$$

$$\underline{P_{CR} = 278139.8\ N}$$

STATIC LOAD OF FLYWHEEL ITSELF

$$F = mg = (21.038\,kg)(9.81\,m/s^2) = \underline{206.38\ N}$$

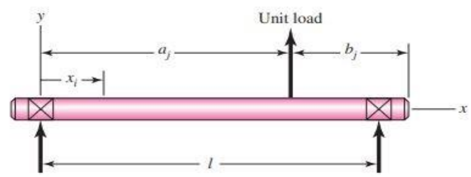
∴ OUR LOADING IS WELL BELOW BUCKLING, MAY LATER NEED TO LOOK AT LOAD CASE FOR BENDING IF THERE'S MISALIGNMENT DURING USE.

Appendix K. Critical Shaft Speed Calculations

	US Standard		Metric	
B	8.31	in	2.11E-01	meters
X	5.1	in	1.30E-01	meters
E	27600000	lbf/in^2	1.90E+11	Nm^2
I	0.040212386	in^4	1.67E-08	m^4
L	14.91	in	3.79E-01	meters
delta	5.4313E-05	in/lbf	3.10E-07	m/N
Mass (AL)	45.03	lb	2.04E+01	kg
Mass (St)	0.90	lb	4.07E-01	kg
Mass Force	1477.71	lbf	2.04E+02	N
	Omega_critical		393.42	rad/s
			3756.86	RPM

Figure 7–13

The influence coefficient δ_{ij} is the deflection at i due to a unit load at j.

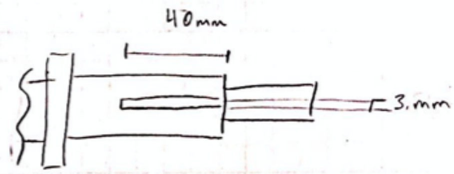


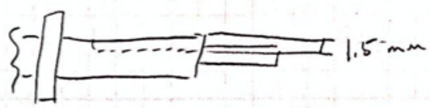
$$\omega_1 = \left(\frac{\pi}{l}\right)^2 \sqrt{\frac{EI}{m}} = \left(\frac{\pi}{l}\right)^2 \sqrt{\frac{gEI}{A\gamma}} \qquad (7\text{–}22)$$

$$\delta_{ij} = \begin{cases} \dfrac{b_j x_i}{6EIl}(l^2 - b_j^2 - x_i^2) & x_i \le a_i \\ \dfrac{a_j(l - x_i)}{6EIl}(2lx_i - a_j^2 - x_i^2) & x_i > a_i \end{cases} \qquad (7\text{–}24)$$

Appendix L. Hand Calculations for Machine Key Shear Calculations

KEYSTOCK, SHEAR CALCS





SHEAR FORCE IS FROM TORQUE ON FLYWHEEL

$$\tau = \frac{VQ}{It}$$

ASSUME DIRECT SHEAR

$$\tau = \frac{V}{A} = \frac{T \cdot r}{(40 \cdot 3)\,mm^2}$$

ASSUME THAT OUR SYSTEM MOTOR MAX TORQUE IS = .52 Nm
AND GEAR RATIO 5:1 => ON FLYWHEEL = 2.6 Nm

$$\tau = \frac{(2.6\ N \cdot m)\left(\frac{1}{12.5\ mm}\right)}{(40 \cdot 3)\,mm^2} \cdot \left(\frac{1000\ mm}{1\ m}\right)^3$$

$$\tau = 1.73 \times 10^6\ N/m^2$$

YIELD STRENGTH = $5.3 \times 10^8\ N/m^2$

$$\eta = \frac{5.3 \times 10^8}{1.73 \times 10^6} = \boxed{305.77}$$

Appendix M.

Materials Budget for Senior Project

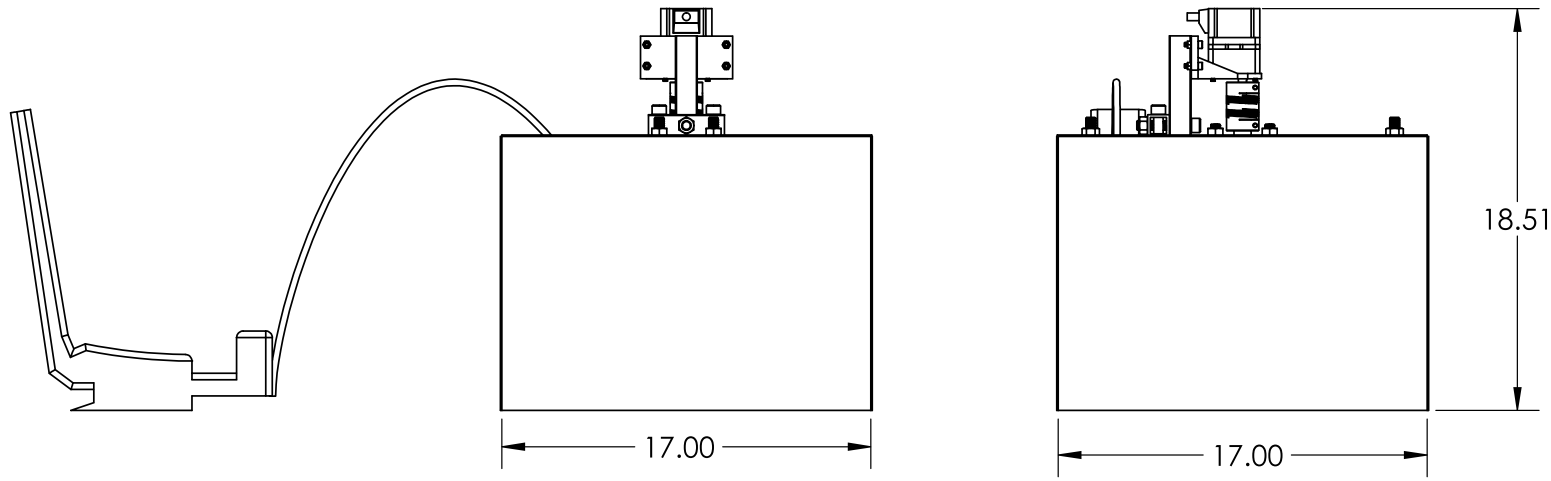
Title of Senior Project:	F51 - Sustainable Energy Storage
Team members:	Jake Grillo, Alyse Coonce, Nick Schnorr, Jack Linchey
Designated Team Treasurer:	Jack Linchey
Faculty Advisor:	Professor Peter Schuster
Sponsor:	Mr. Harish Butani / Dr. Mohammed Noori
Quarter and year project began:	Fall 2020
Materials budget given for this project:	**$2,500.00**

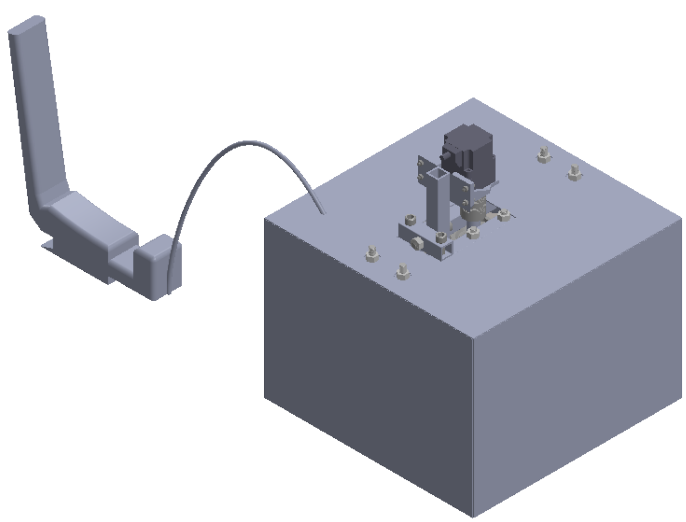
Part Number	Item Description	Vendor	Vendor Part Number	Quantity	Unit Material Cost	Shipping Estimate	Handling Estimate	Tax Estimate	Total Cost
11100	Flywheel	McCarthy Steel	-	1	$ 350.00	$ -	$ -	$ -	$ 350.00
11200	Shaft	Misumi	N/A	1	$ 50.00	$ 16.00	$ -	$ -	$ 66.00
11300	Retaining ring	McMaster	97633A300	1	$ 9.27	$ 1.00	$ -	$ -	$ 10.27
11400	Flywheel Bolts - 60mm	McMaster	92095A442	4	$ 3.57	$ 1.00	$ -	$ -	$ 15.28
11500	Machine Key	McMaster	98870A143	1	$ 8.36	$ 1.00	$ -	$ -	$ 9.36
12100	Brake Rotor & Pads	Summit Racing	PWR-KOE772	1	$ 67.99	$ -	$ -	$ 6.66	$ 74.65
12200	Hydraulic Handbrake	Amazon	B005-BLACK	1	$ 41.99	$ -	$ -	$ 3.46	$ 45.45
12300	Brake Line Fittings	Summit Racing	EAR-581533ERL	1	$ 10.64	$ -	$ -	$ 1.04	$ 11.68
12400	Brake Line	Summit Racing	ZEX-NS6670CB	1	$ 17.99	$ -	$ -	$ 1.76	$ 19.75
12500	Caliper	Summit Racing	L1378A	1	$ 47.99	$ -	$ 41.00	$ 4.70	$ 93.69
12600	Brake Spacer	McMaster	1610T49	1	$ 21.82	$ 1.00	$ -	$ -	$ 22.82
13100	25mm Radial Bearings	McMaster	5967K84	1	$ 60.47	$ 1.00	$ -	$ -	$ 61.47
13200	20mm Radial Bearings	McMaster	5967K82	1	$ 88.30	$ 1.00	$ -	$ -	$ 89.30
13300	Housing Bolts	McMaster	91251A004	1	$ 9.72	$ 1.00	$ -	$ -	$ 10.72
13400	Housing Nuts	McMaster	95479A215	1	$ 9.49	$ 1.00	$ -	$ -	$ 10.49
13500	Thrust Bearing Housing	McMaster	1388K504	1	$ 37.66	$ 1.00	$ -	$ -	$ 38.66
13600	Thrust Bearing	Motion Industries	NTA-1018	1	$ 3.76	$ 14.46	$ -	$ 0.58	$ 18.80
14100	Motor and Controller	OrientalMotor	BLHM230KC-5 & BLH2D30-KD	1	$ 433.00	$ -	$ -	$ -	$ 433.00
14200	Shaft Coupler	OrientalMotor	MCS401020	1	$ 76.00	$ -	$ -	$ -	$ 76.00
14300	Motor Mounting Bracket	OrientalMotor	SOL2A-A	1	$ 27.00	$ -	$ -	$ -	$ 27.00
14400	M5 16mm Bolts	McMaster	91292A126	1	$ 11.29	$ 1.00	$ -	$ -	$ 12.29
14500	2.5" Large Bolts	McMaster	91251A005	1	$ 8.79	$ 1.00	$ -	$ -	$ 9.79
14600	M5 Nuts	McMaster	90592A095	1	$ 1.76	$ 1.00	$ -	$ -	$ 2.76
14700	Square Tube Stock (3.5")	McCarthy Steel	-	2	$ 0.73	$ -	$ -	$ -	$ 1.46
14800	Square Tube Stock (6.6")	McCarthy Steel	-	1	$ 1.38	$ -	$ -	$ -	$ 1.38
14900	Mounting Plate	McCarthy Steel	-	1	$ 1.38	$ -	$ -	$ -	$ 1.38
15200A	Square Tube Stock (10.5")	McCarthy Steel	-	4	$ 2.19	$ -	$ -	$ -	$ 8.76
15200B	Square Tube Stock (10.5" w/ holes)	McCarthy Steel	-	8	$ 2.50	$ -	$ -	$ -	$ 20.00
15300A	Square Tube Stock (15" Upper)	McCarthy Steel	-	2	$ 3.13	$ -	$ -	$ -	$ 6.26
15300B	Square Tube Stock (15" Lower)	McCarthy Steel	-	2	$ 3.13	$ -	$ -	$ -	$ 6.26
15300C	Square Tube Stock (15" Caliper)	McCarthy Steel	-	1	$ 3.13	$ -	$ -	$ -	$ 3.13
15400	Square Tube Stock (16")	McCarthy Steel	-	8	$ 3.33	$ -	$ -	$ -	$ 26.64
15500	7/16" x 20, Screw 1"	McMaster	90128A402	2	$ 7.63	$ 1.00	$ -	$ -	$ 16.26
15600A	Back Angle Iron 1" x 1" (17")	McMaster	9017K444	1	$ 8.99	$ 1.00	$ -	$ -	$ 9.99
15600B	Front Angle Iron 1" x 1" (17")	McMaster	9017K444	1	$ 8.99	$ 1.00	$ -	$ -	$ 9.99
15700A	Side Steel Plate	McCarthy Steel	-	4	$ 15.00	$ -	$ -	$ -	$ 60.00
15700B	Top Steel Plate	McCarthy Steel	-	1	$ 15.00	$ -	$ -	$ -	$ 15.00
16100	Tachometer	MPJA	35029 MP	1	$ 3.00	$ 6.95	$ -	$ -	$ 9.95
16210	Receiver	Amazon	B01EE4VXS0	1	$ 2.00	$ -	$ -	$ 1.50	$ 3.50
16220	Transmitter	Amazon	B01EE4VXS0	1	$ 2.00	$ -	$ -	$ 1.50	$ 3.50
16230	Buttons	Sparkfun	COM-09336	3	$ 3.00	$ 1.50	$ 2.00	$ -	$ 12.50
16240	Switches	Sparkfun	COM-11310	2	$ 3.00	$ 1.50	$ 2.00	$ -	$ 9.50
16300	Charge controller	Amazon	B072MMDY4F	1	$ 16.00	$ -	$ -	$ 1.50	$ 17.50
16400	Relay	Sparkfun	COM-15093	4	$ 12.95	$ 1.50	$ 2.00	$ -	$ 55.30
16500	Rectifier	Sparkfun	B01JKRIPUK	1	$ 12.49	$ 1.50	$ 2.00	$ -	$ 15.99
16600	Jumper Wire Kit	Amazon	PRT-11709	1	$ 5.89	$ -	$ -	$ 1.50	$ 7.39
16700	Wire spool	Amazon	55667423	1	$ 9.16	$ -	$ -	$ 1.50	$ 10.66
								Total	$ 1,841.54
								Budget	$2,500.00
								Remaining Budget	$658.46

Appendix N: Drawing Package

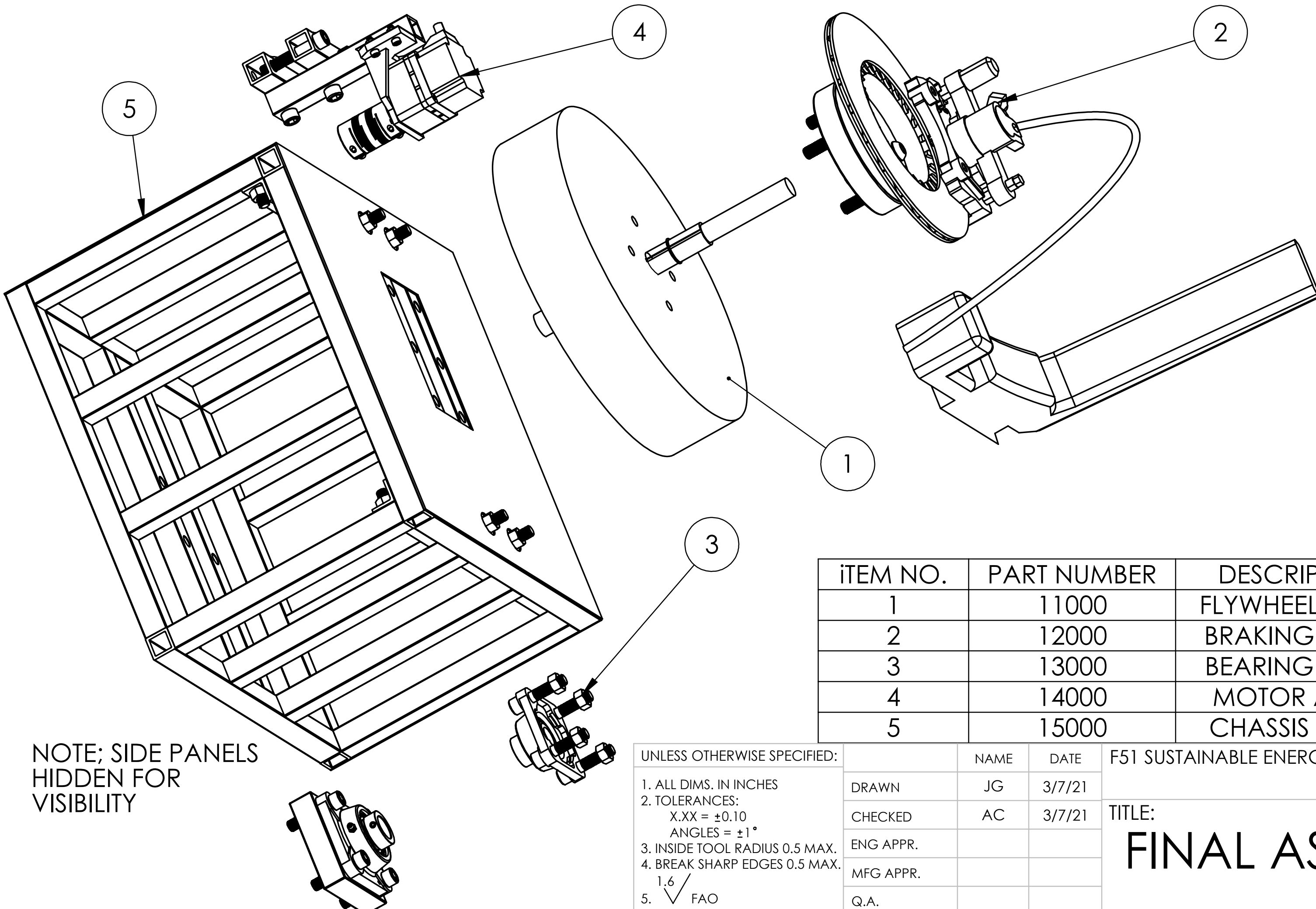
Assembly Level	Part Number	Description				Qty	Cost	Ttl Cost	Source	More Info
		Lvl0	Lvl1	Lvl2	Lvl3					
0	10000	Final Assembly						—		
1	11000		Flywheel Assy					—		
2	11100			Flywheel		1	$370.00	$370.00	McCarthy Steel	Customized piece
2	11200			Shaft		1	$ 50.00	$50.00	Misumi	Customized piece directly from Misumi
2	11300			Retaining ring		1	$ 9.27	$9.27	McMaster	Item 97633A300 (Pack of 50)
2	11400			Machine Key		1	$ 8.36	$8.36	McMaster	Item 98870A143 (Pack of 5)
1	12000		Braking Assy					—		
2	12100			Brake Rotor & Pads		1	$ 67.99	$67.99	Summit Racing	PWR-KOE772
2	12200			Hydraulic Handbrake		1	$ 41.99	$41.99	Amazon	B005-BLACK
2	12300			Brake Line Fittings		1	$ 10.64	$10.64	Summit Racing	EAR-581533ERL
2	12400			Brake Line		1	$ 17.99	$17.99	Summit Racing	ZEX-NS6670CB
2	12500			Caliper		1	$ 47.99	$47.99	Summit Racing	Item L1378A
2	12600			Brake Spacer		1	$ 21.82	$21.82	McMaster	Item 1610T49
2	12700			Flywheel Bolts - 60mm		4	$ 3.57	$14.28	McMaster	Item 92095A442
1	13000		Bearing Assy					—		
2	13100			25mm Radial Bearings		1	$ 60.47	$60.47	McMaster	Item 5967K84
2	13200			20mm Radial Bearings		1	$ 88.30	$88.30	McMaster	Item 5967K82
2	13300			Housing Bolts		1	$ 9.72	$9.72	McMaster	Item 91251A004 (10 Pack)
2	13400			Housing Nuts		1	$ 9.49	$9.49	McMaster	Item 95479A215 (25 Pack)
2	13500			Thrust Bearing Housing		1	$ 37.66	$37.66	McMaster	Item 1388K504
2	13600			Thrust Bearing		1	$ 3.76	$3.76	Motion Industries	Item NTA-1018
1	14000		Motor Assy					—		
2	14100			Motor and Controller		1	$433.00	$433.00	OrientalMotor	Item BLHM230KC-5 / BLH2D30-KD
2	14200			Shaft Coupler		1	$ 76.00	$76.00	OrientalMotor	Item MCS401020
2	14300			Motor Mounting Bracket		1	$ 27.00	$27.00	OrientalMotor	Item SOL2A-A
2	14400			M5 16mm Bolts		1	$ 11.29	$11.29	McMaster	Item 91292A126 (100 Pack)
2	14500			2.5" Large Bolts		1	$ 8.79	$8.79	McMaster	Item 91251A005 (5 Pack)
2	14600			M5 Nuts		1	$ 1.76	$1.76	McMaster	Item 90592A095 (100 Pack)
2	14700			Square Tube Stock (3.5")		2	$ 0.73	$1.46	McCarthy Steel	
2	14800			Mounting Plate Sub-Assy						
3	14810				Square Tube Stock (6.6")	1	$ 1.38	$1.38	McCarthy Steel	
3	14820				Mounting Plate	1	$ 1.38	$1.38	McCarthy Steel	Recycle from Top steel Plate Cut
1	15000		Chassis Assy					—		
2	15100			7/16"-20 Nut		1	$11.80	$11.80	Mcmaster	Item 95479A215 - Extra from Bearing Asym
1	15200			Welded Frame Sub-Assy						
3	15210				Square Tube Stock (10.5")	4	$ 2.19	$8.75	McCarthy Steel	10.5" Length w/ no holes
3	15220				Square Tube Stock (10.5" w/ holes)	8	$ 2.50	$20.00	McCarthy Steel	10.5" Length w/ top hole for Angle Iron
3	15230				Square Tube Stock (15" Lower)	2	$ 3.13	$6.25	McCarthy Steel	
3	15240				Square Tube Stock (16")	8	$ 3.33	$26.67	McCarthy Steel	
2	15300			Welded H Sub-Assy						
3	15310				Square Tube Stock (15" Caliper)	1	$ 3.13	$3.13	McCarthy Steel	
3	15320				Back Angle Iron 1" x 1" (17")	1	$ 8.99	$8.99	McMaster	Backside with 4 holes - 9017K444
3	15330				Front Angle Iron 1" x 1" (17")	1	$ 8.99	$8.99	McMaster	Frontside with 4 holes - 9017K444
2	15400			Square Tube Stock (15" Upper)		2	$ 3.13	$6.25	McCarthy Steel	
2	15500			7/16" x 20, Screw 1"		2	$ 7.63	$15.26	McMaster	Item 90128A402 (10 Pack)

Assembly Level	Part Number	Description	Qty	Cost	Ttl Cost	Source	More Info
		Lvl0 Lvl1 Lvl2 Lvl3					
2	15700A	Side Steel Plate - Plain	4	$ 15.00	$60.00	McCarthy Steel	
2	15700B	Top Steel Plate	1	$ 15.00	$15.00	McCarthy Steel	
1	16000	Control System Assy			----		
2	16100	Tachometer	1	$ 3.00	$3.00	MPJA	Item 35029 MP
2	16200	Input System Assy			----		
3	16210	Receiver	1	$ 2.00	$2.00	Amazon	Item B01EE4VXS0
3	16220	Transmitter	1	$ 2.00	$2.00	Amazon	Item B01EE4VXS0
3	16230	Buttons	3	$ 3.00	$9.00	Sparkfun	Item COM-09336
3	16240	Switches	2	$ 3.00	$6.00	Sparkfun	Item COM-11310
2	16300	Charge controller	1	$ 16.00	$16.00	Amazon	Item B072MMDY4F
2	16400	Relay	4	$ 12.95	$51.80	Sparkfun	Item COM-15093
2	16500	Rectifier	1	$ 12.49	$12.49	Amazon	Item B01JKRIPUK
2	16600	Jumper Wire Kit	1	$ 5.89	$5.89	Amazon	Item PRT-11709
2	16700	Wire spool	1	$ 9.16	$9.16	Amazon	Item 55667423
Totals		Parts	80	Cost	$1,731.04		





UNLESS OTHERWISE SPECIFIED:		NAME	DATE	F51 SUSTAINABLE ENERGY STORAGE
1. ALL DIMS. IN INCHES 2. TOLERANCES: X.XX = ±0.10 ANGLES = ±1° 3. INSIDE TOOL RADIUS 0.5 MAX. 4. BREAK SHARP EDGES 0.5 MAX. 5. 1.6 √ FAO	DRAWN	JG	3/7/21	TITLE:
	CHECKED	AC	3/7/21	FINAL ASSEMBLY
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL N/A	COMMENTS:			SIZE A · DWG. NO. 10000 · REV A
DO NOT SCALE DRAWING				SCALE: 1:8 · SHEET 1 OF 1



NOTE; SIDE PANELS HIDDEN FOR VISIBILITY

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	11000	FLYWHEEL ASYM	1
2	12000	BRAKING ASYM	1
3	13000	BEARING ASYM	1
4	14000	MOTOR ASYM	1
5	15000	CHASSIS ASYM	1

UNLESS OTHERWISE SPECIFIED:

1. ALL DIMS. IN INCHES
2. TOLERANCES:
   X.XX = ±0.10
   ANGLES = ±1°
3. INSIDE TOOL RADIUS 0.5 MAX.
4. BREAK SHARP EDGES 0.5 MAX.
5. 1.6 √ FAO

MATERIAL: N/A

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JG	3/7/21
CHECKED	AC	3/7/21
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

F51 SUSTAINABLE ENERGY STORAGE

TITLE:

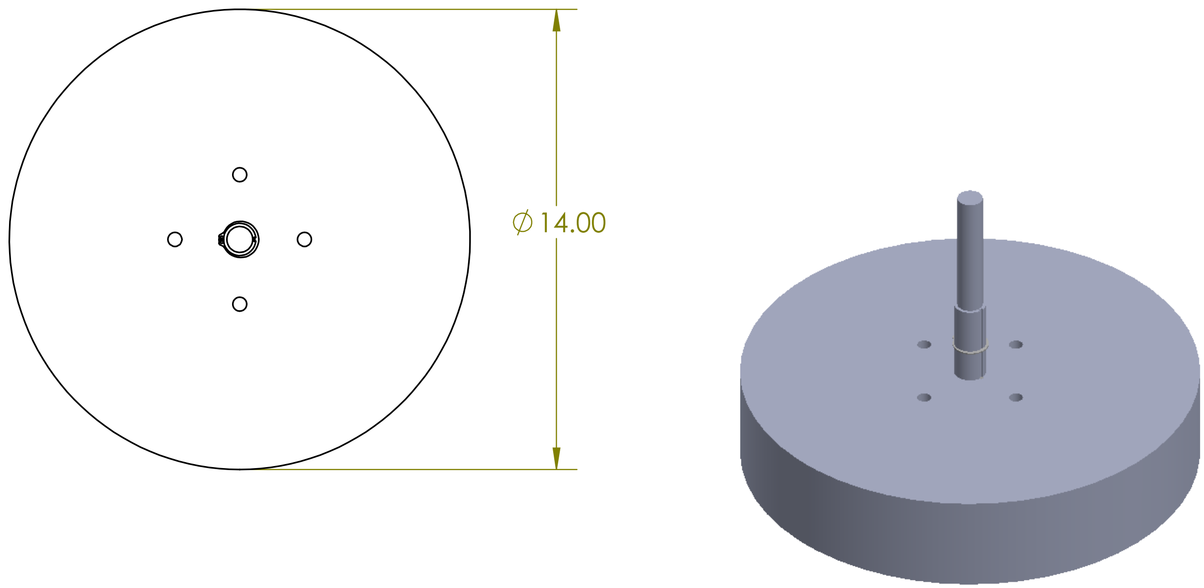
FINAL ASSEMBLY

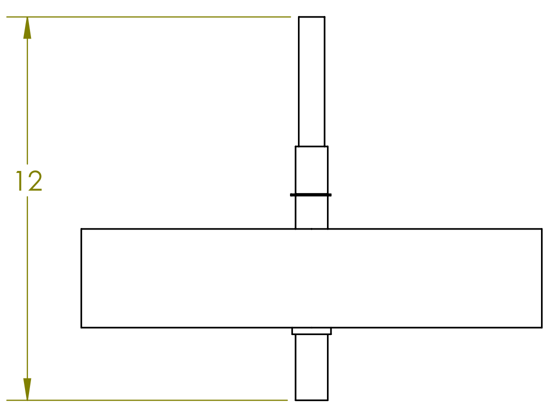
SIZE	DWG. NO.	REV
A	10000E	A

SCALE: 1:16 SHEET 1 OF 1

2 1

B



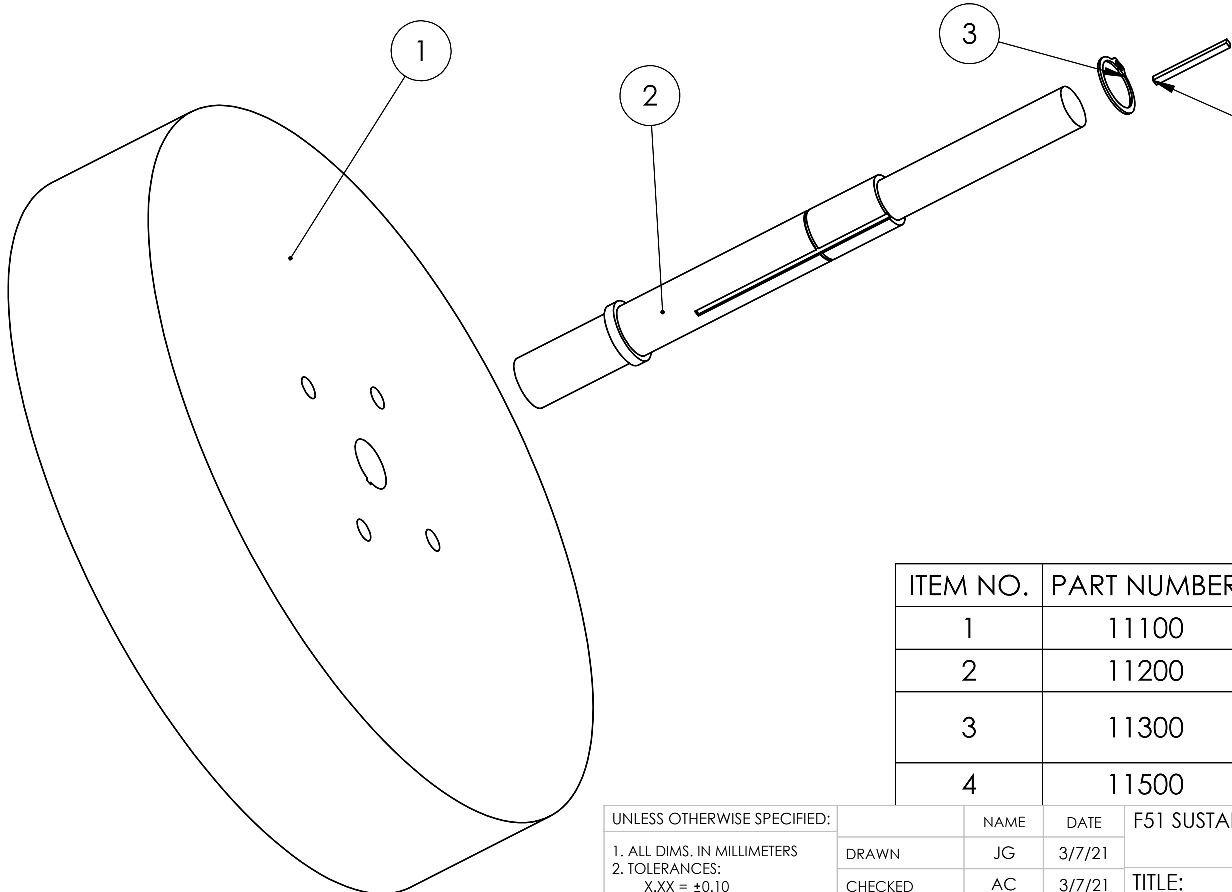


A

UNLESS OTHERWISE SPECIFIED:		NAME	DATE	F51 SUSTAINABLE ENERGY STORAGE
1. ALL DIMS. IN INCHES 2. TOLERANCES: X.XX = ±0.10 ANGLES = ±1° 3. INSIDE TOOL RADIUS 0.5 MAX. 4. BREAK SHARP EDGES 0.5 MAX. 5. 1.6 √ FAO	DRAWN	JG	3/7/21	TITLE:
	CHECKED	AC	3/7/21	FLYWHEEL ASSEMBLY
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL N/A	COMMENTS:			
DO NOT SCALE DRAWING				

SIZE	DWG. NO.	REV
A	11000	A
SCALE: 1:10		SHEET 1 OF 1

B A 2 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	11100	FLYWHEEL	1
2	11200	SHAFT	1
3	11300	RETAINING RING	1
4	11500	MACHINE KEY	1

UNLESS OTHERWISE SPECIFIED:

1. ALL DIMS. IN MILLIMETERS
2. TOLERANCES:
   X.XX = ±0.10
   ANGLES = ±1°
3. INSIDE TOOL RADIUS 0.5 MAX.
4. BREAK SHARP EDGES 0.5 MAX.
5. 1.6 √ FAO

MATERIAL: N/A

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JG	3/7/21
CHECKED	AC	3/7/21
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

F51 SUSTAINABLE ENERGY STORAGE

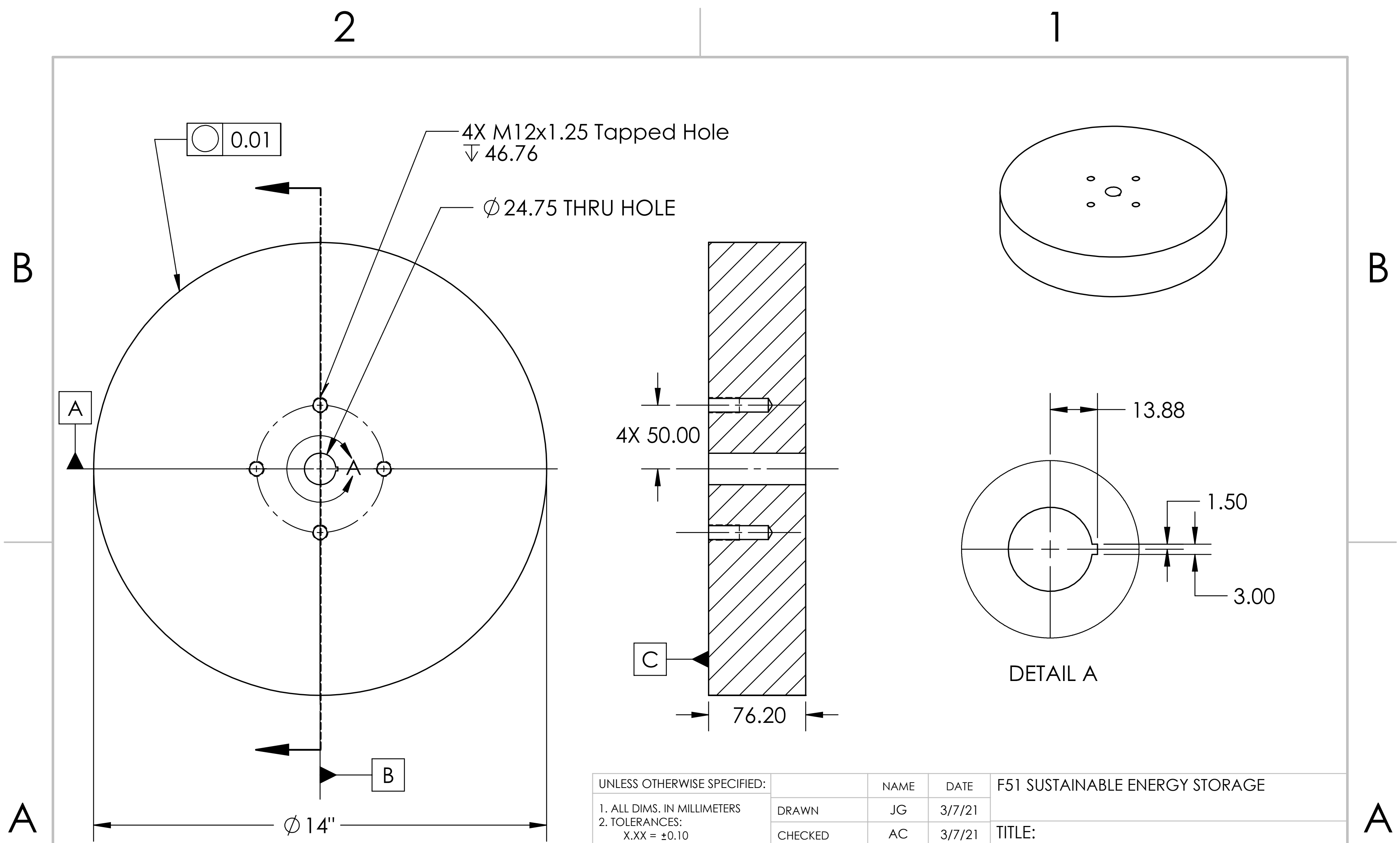
TITLE:

FLYWHEEL ASSEMBLY

SIZE	DWG. NO.	REV
A	11000E	A

SCALE: 1:10

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

1. ALL DIMS. IN MILLIMETERS
2. TOLERANCES:
   X.XX = ±0.10
   ANGLES = ±1°
3. INSIDE TOOL RADIUS 0.5 MAX.
4. BREAK SHARP EDGES 0.5 MAX.
5. 1.6 √ FAO

MATERIAL
6061 ALUMINUM

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JG	3/7/21
CHECKED	AC	3/7/21
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

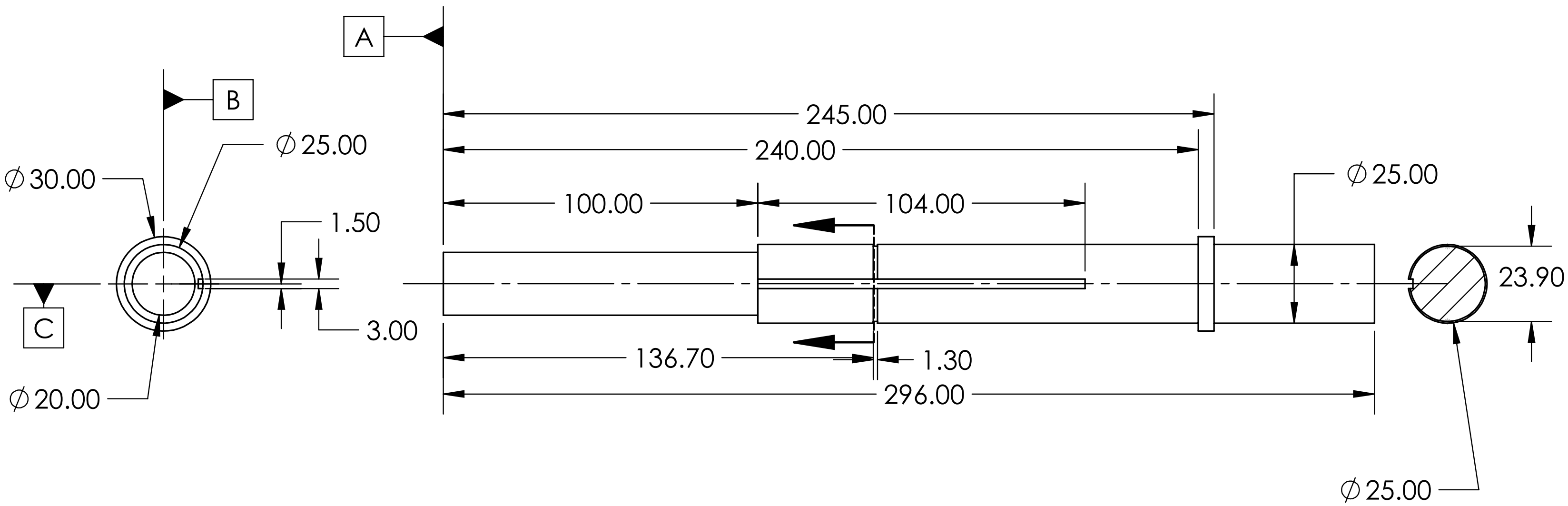
F51 SUSTAINABLE ENERGY STORAGE

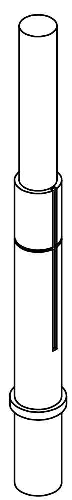
TITLE:

FLYWHEEL

SIZE	DWG. NO.	REV
A	11100	A

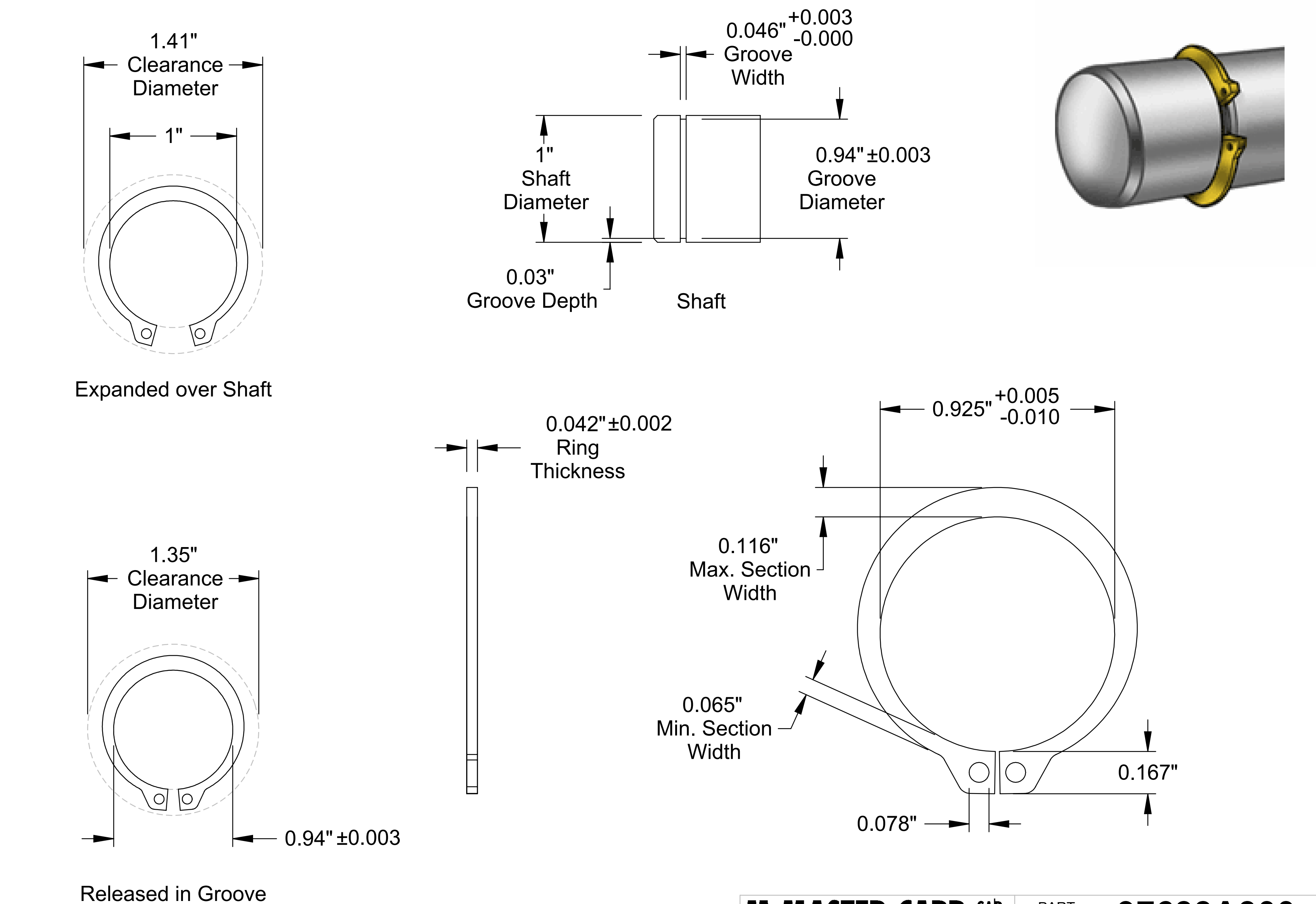
SCALE: 1:8 SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED:		NAME	DATE	F51 SUSTAINABLE ENERGY STORAGE
1. ALL DIMS. IN MILLIMETERS 2. TOLERANCES: X.XX = ±0.10 ANGLES = ±1° 3. INSIDE TOOL RADIUS 0.5 MAX. 4. BREAK SHARP EDGES 0.5 MAX. 5. 1.6 √ FAO	DRAWN	JG	3/7/21	
	CHECKED	AC	3/7/21	TITLE: SHAFT
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL 1045 CARBON STEEL	COMMENTS:			SIZE A · DWG. NO. 11200 · REV A
DO NOT SCALE DRAWING				SCALE: 1:8 · SHEET 1 OF 1

PART NUMBER: 11300



Note: Clearance diameter is the diameter of a housing that can pass freely over the ring.

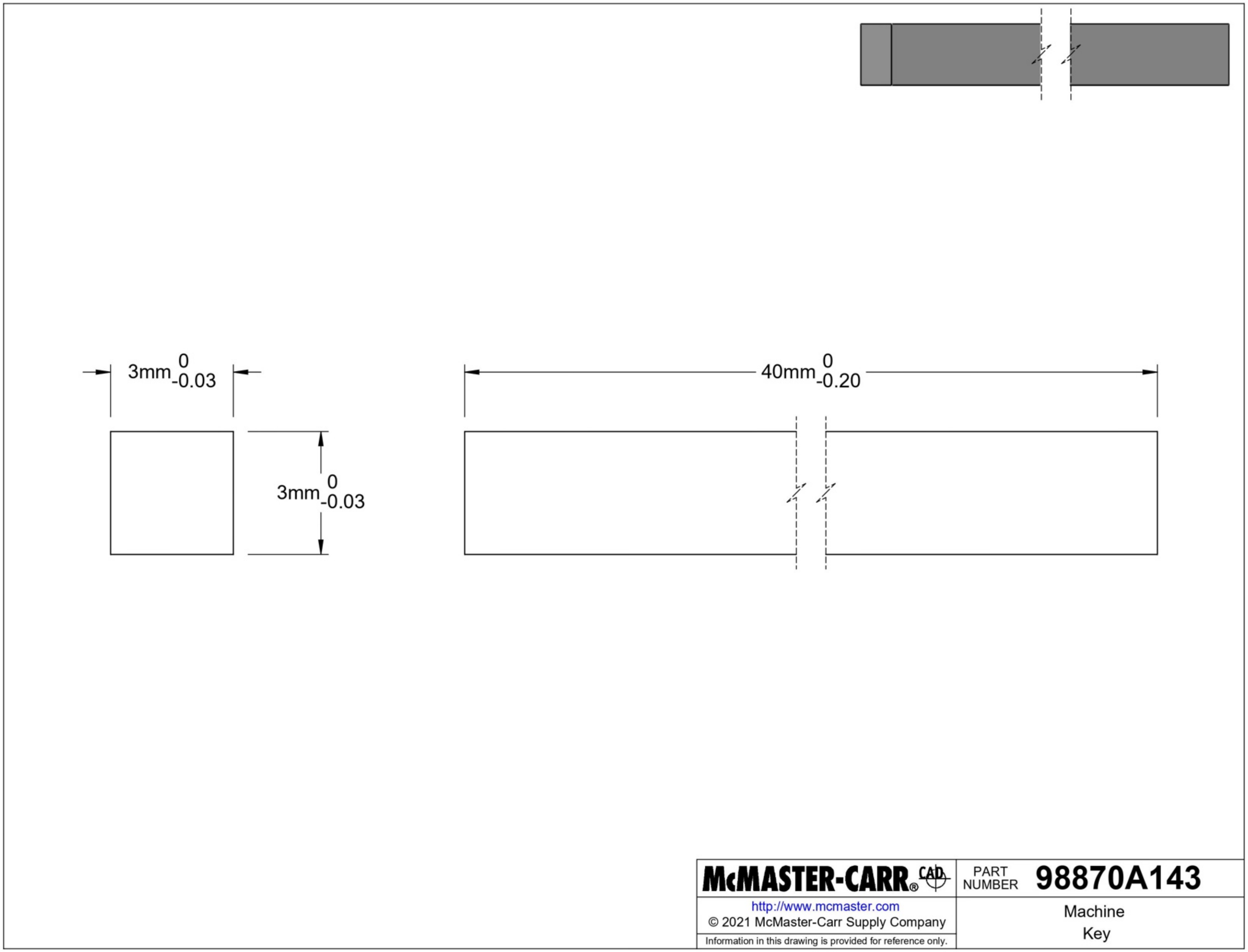
McMASTER-CARR® CAD

http://www.mcmaster.com

PART NUMBER 97633A300

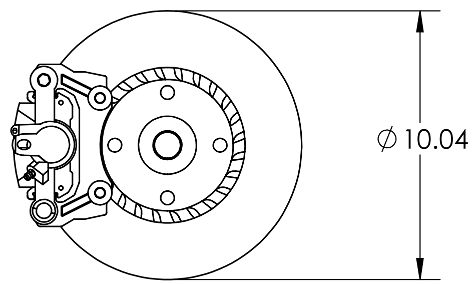
Black-Finish Steel
External Retaining Ring

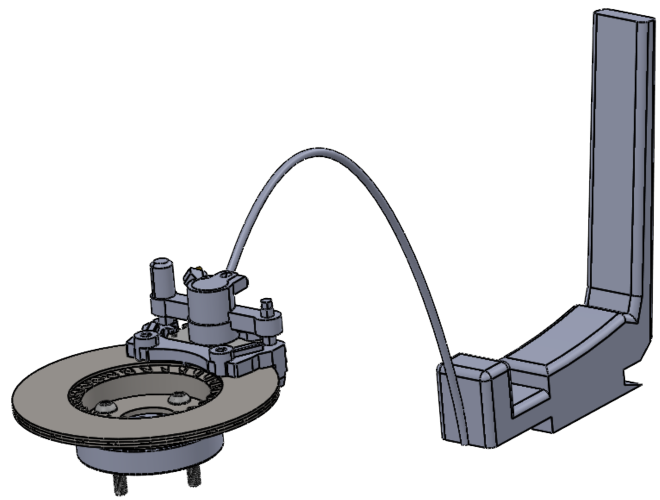
PART NUMBER: 11400



2 1

B





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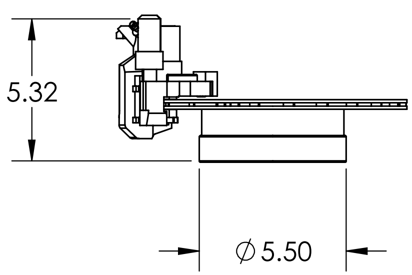


A

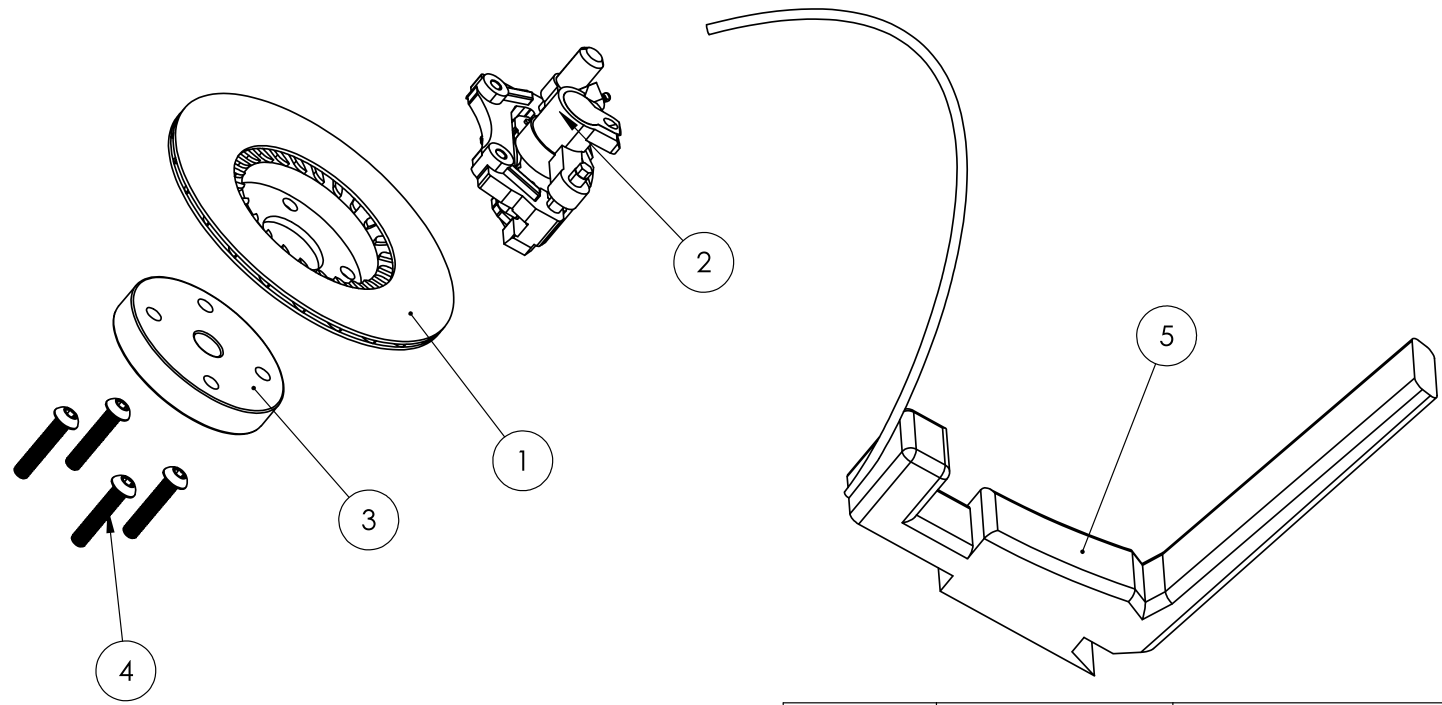
UNLESS OTHERWISE SPECIFIED:		NAME	DATE	F51 SUSTAINABLE ENERGY STORAGE
1. ALL DIMS. IN INCHES 2. TOLERANCES: X.XX = ±0.10 ANGLES = ±1° 3. INSIDE TOOL RADIUS 0.5 MAX. 4. BREAK SHARP EDGES 0.5 MAX. 5. 1.6 √ FAO	DRAWN	JG	3/7/21	TITLE:
	CHECKED	AC	3/7/21	BRAKING ASSEMBLY
	ENG APPR.			
	MFG APPR.			
	Q.A.			
	COMMENTS:			SIZE A DWG. NO. 12000 REV A
MATERIAL N/A				
DO NOT SCALE DRAWING				SCALE: 1:8 SHEET 1 OF 1

A

2 1

2 1

B B



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	12100	BRAKE ROTOR	1
2	12500	BRAKE CALIPER	1
3	12600	BRAKE SPACER	1
4	12700	FLYWHEEL BOLTS	4
5	12200	HAND BRAKE	1

A A

UNLESS OTHERWISE SPECIFIED:

1. ALL DIMS. IN INCHES
2. TOLERANCES:
   X.XX = ±0.10
   ANGLES = ±1°
3. INSIDE TOOL RADIUS 0.5 MAX.
4. BREAK SHARP EDGES 0.5 MAX.
5. 1.6 √ FAO

MATERIAL N/A

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JG	3/7/21
CHECKED	AC	3/7/21
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

F51 SUSTAINABLE ENERGY STORAGE

TITLE:

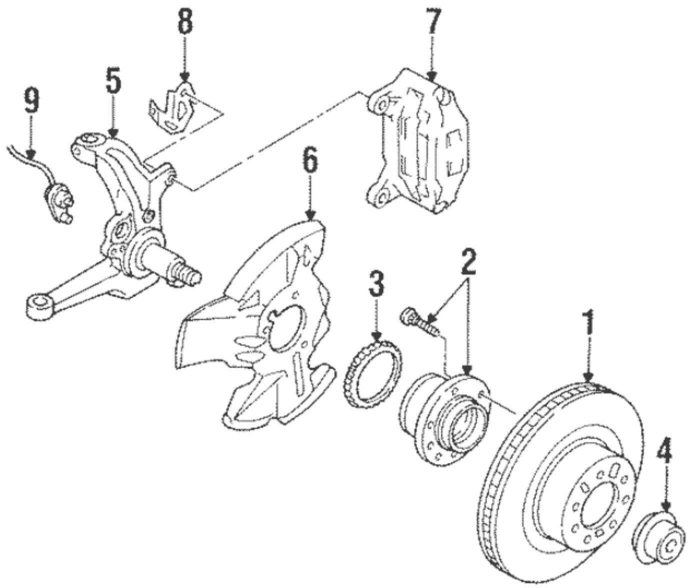
BRAKING ASSEMBLY

SIZE	DWG. NO.	REV
A	12000E	A

SCALE: 1:50 SHEET 1 OF 1

2 1

PART NUMBER: 12100



DESCRIPTION:

Mazda Miata Rear Brake Rotor from NA Generation (1989 – 1997)

Bolt Pattern: 4x 100mm, M12 Bolt holes

Outside Diameter: 251mm

Rotor Thickness: 0.35in

Rotor Material: Iron

Nominal Thickness: 20mm

Rotor Construction: Vented

PART NUMBER: 12200

<u>DESCRIPTION:</u>
Universal Hydraulic Handbrake with Oil Reservoir
Handle Lever Length: 11.69”
Master Cylinder Pressure: 0.75 Bar
Cylinder size: ¾ Scale
Overall Dimensions: 12.4” x 12.4” x 3.7”
Total Weight: 2.65 lbs
Line Fittings: 3/8-24 Thread

PART NUMBER: 12300

DESCRIPTION:

3/8in-24 Inverted Flare Male Brake Line Fittings

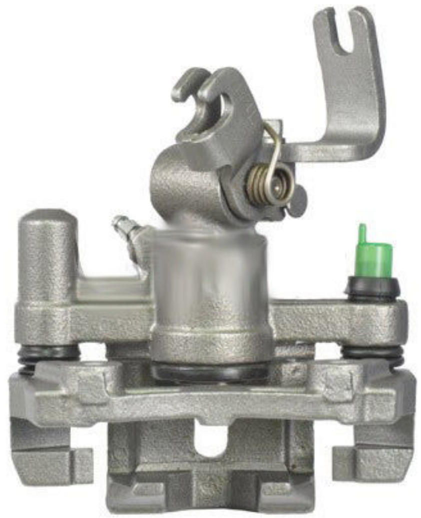
Fitting Angle: Straight
Fitting Size: -3 AN
Fitting Material: Steel
Fitting Finish: Nickel Plated
Package Quantity: 2

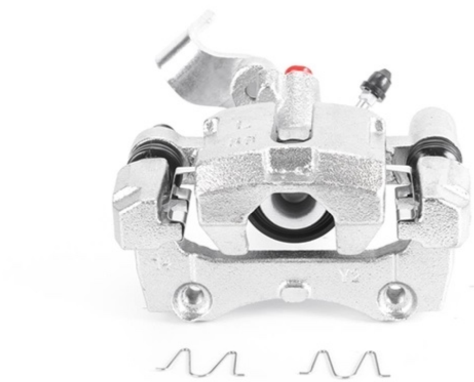
PART NUMBER: 12400

DESCRIPTION:

Stainless Steel Braided Hoses
Hose Size: -3 AN
Hose End Attachment: Female Threads
Hose End Angle: Straight
Fitting Material: Aluminum
Fitting Finish: Polished
Hole Length: 36”
Hose Material: Braided Stainless Steel
Lining Material: PTFE

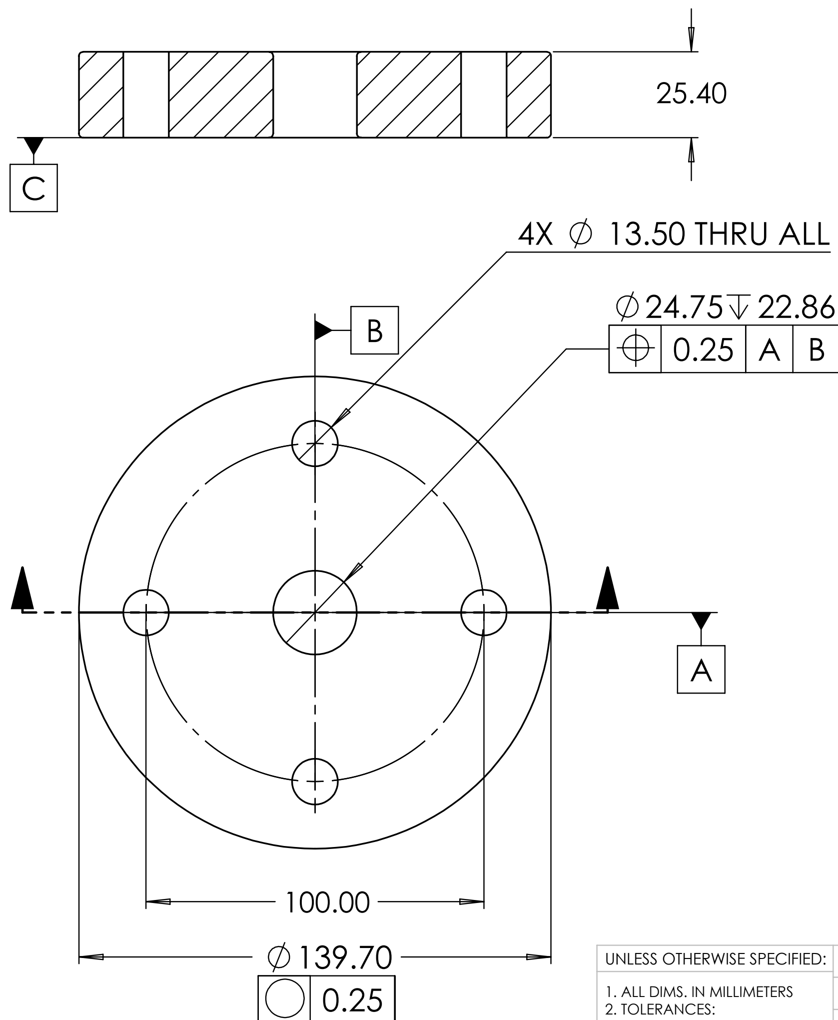
PART NUMBER: 12500

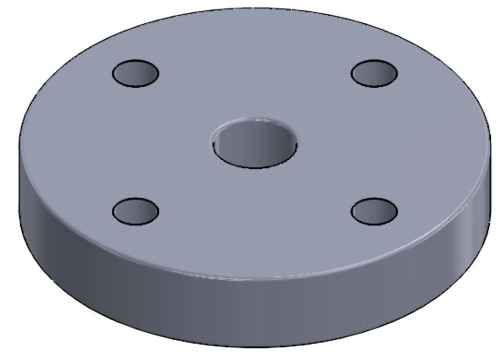




DESCRIPTION:

Mazda Miata NA (1989 - 1997) Brake Caliper for Rear Axle
Piston Diameter: 1.250”
Caliper Material: Cast iron
Caliper Finish: Unfinished
Applications: 1989 – 1996 Mazda Miata US/JPN/EU Spec
Form Factor: Original Equipment Manufacturer

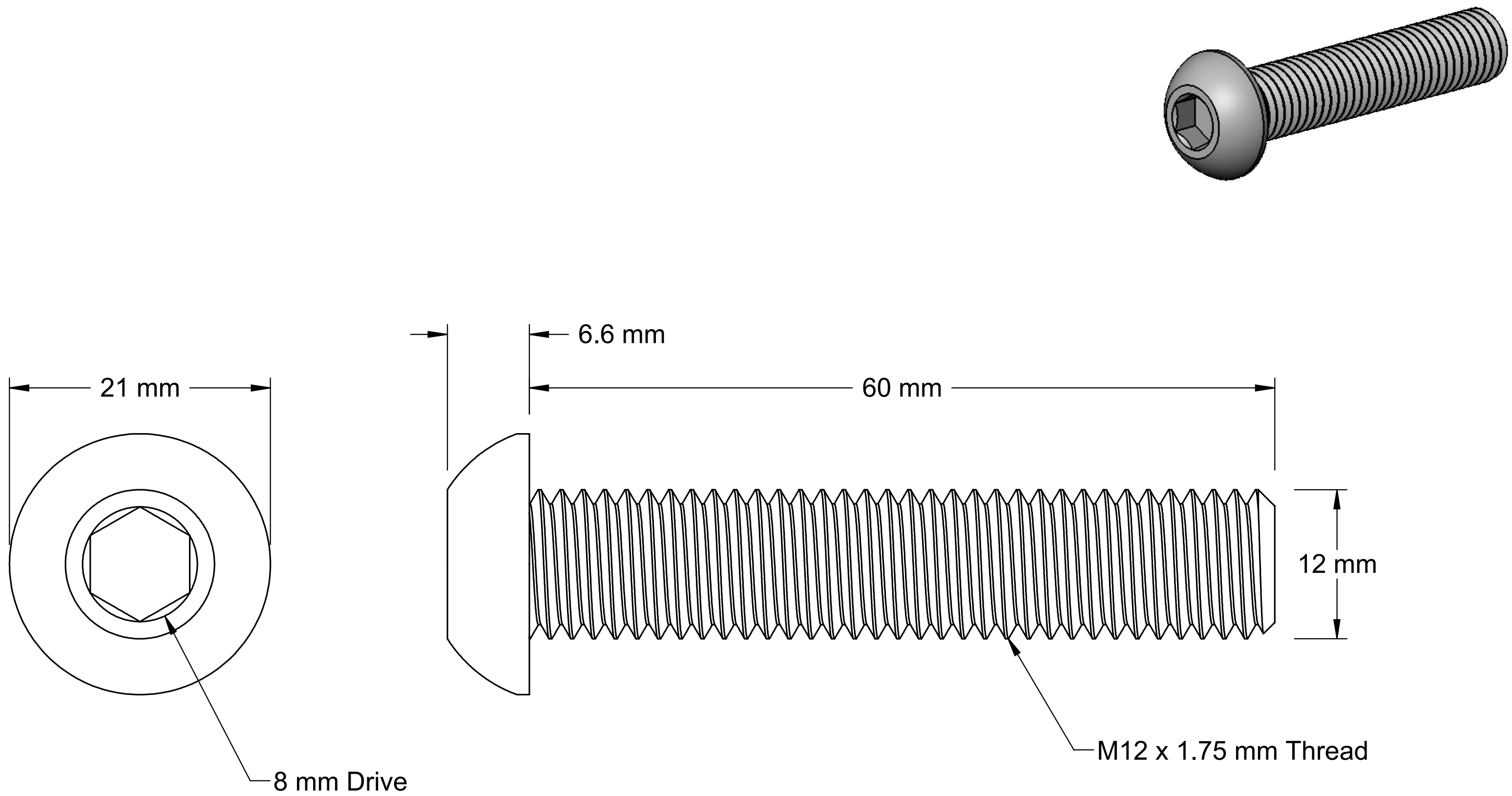




NOTES:
ALL EXTERNAL AND INTERNAL EDGES BREAK WITH A 1.27MM FILLET

UNLESS OTHERWISE SPECIFIED:		NAME	DATE	F51 SUSTAINABLE ENERGY STORAGE
1. ALL DIMS. IN MILLIMETERS 2. TOLERANCES: X.XX = ±0.10 ANGLES = ±1° 3. INSIDE TOOL RADIUS 0.5 MAX. 4. BREAK SHARP EDGES 0.5 MAX. 5. 1.6 √ FAO	DRAWN	JRL	3/8/2021	TITLE:
	CHECKED	JSG	3/8/2021	BRAKE SPACER
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL 6061 ALUMINUM	COMMENTS:			SIZE A · DWG. NO. 12600 · REV A
DO NOT SCALE DRAWING				SCALE: 1:2 · SHEET 1 OF 1

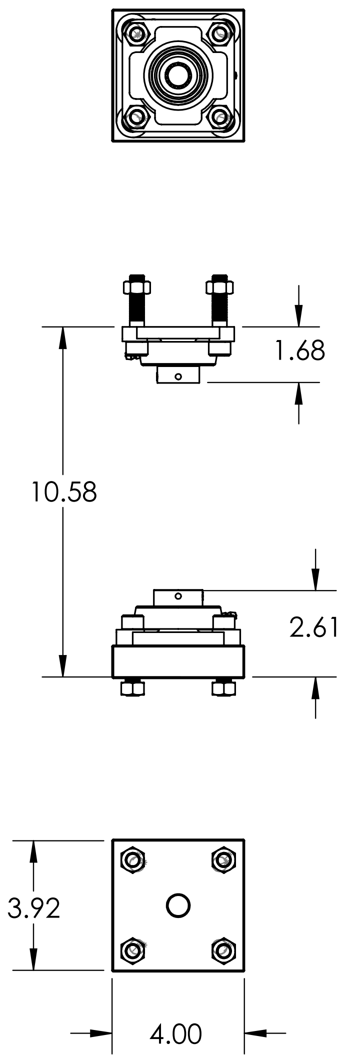
PART NUMBER: 12700

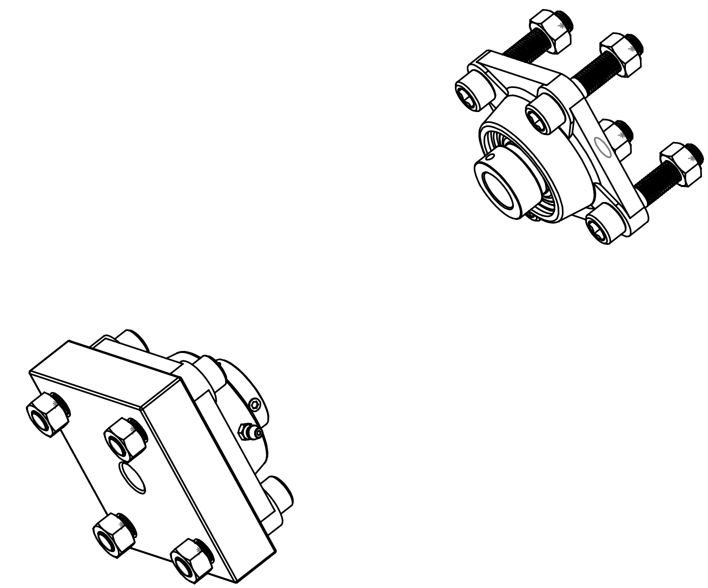


MCMASTER-CARR® CAD	PART NUMBER	92095A442
http://www.mcmaster.com © 2019 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Metric 18-8 Stainless Steel Button Head Hex Drive Screw	

2 1

B B





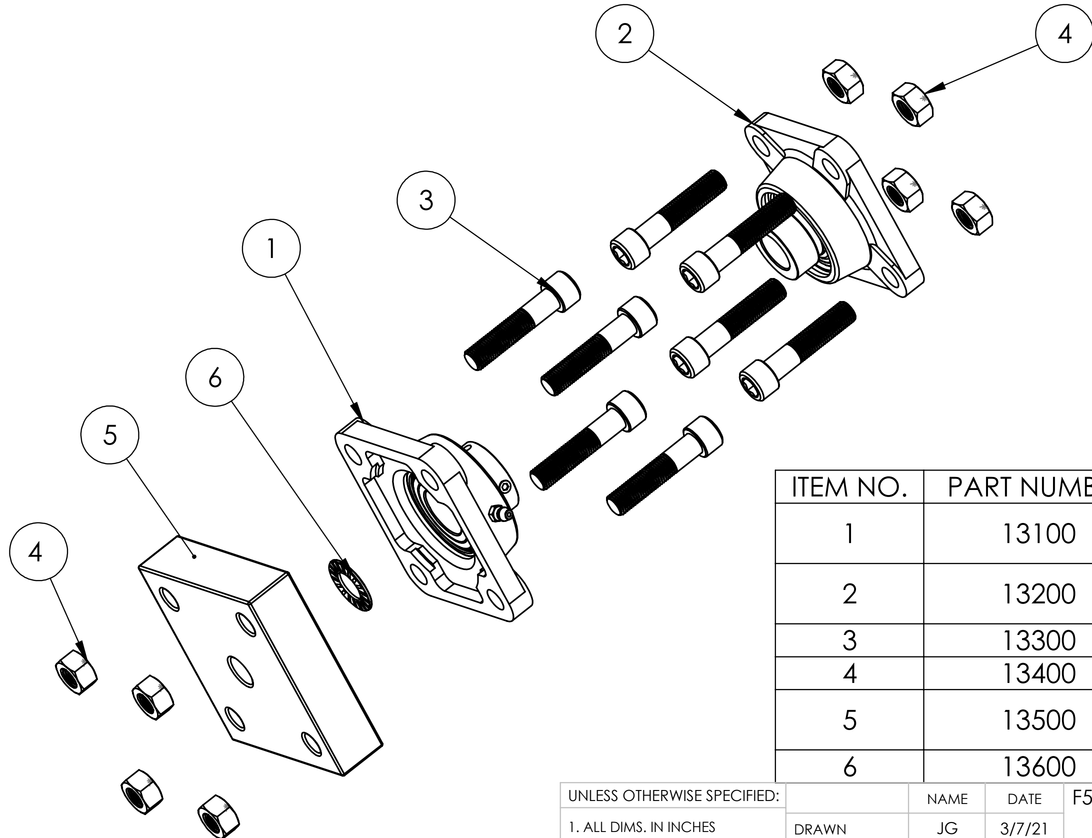
A A

UNLESS OTHERWISE SPECIFIED:		NAME	DATE	F51 SUSTAINABLE ENERGY STORAGE
1. ALL DIMS. IN INCHES 2. TOLERANCES: X.XX = ±0.10 ANGLES = ±1° 3. INSIDE TOOL RADIUS 0.5 MAX. 4. BREAK SHARP EDGES 0.5 MAX. 5. 1.6 √ FAO	DRAWN	JG	3/7/21	
	CHECKED	AC	3/7/21	TITLE:
	ENG APPR.			BEARING ASSEMBLY
	MFG APPR.			
	Q.A.			
MATERIAL N/A	COMMENTS:			SIZE A · DWG. NO. 13000 · REV A
DO NOT SCALE DRAWING				SCALE: 1:8 · SHEET 1 OF 1

2 1

2 1

B B



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	13100	25mm RADIAL BEARING	1
2	13200	20mm RADIAL BEARING	1
3	13300	HOUSING BOLTS	8
4	13400	HOUSING NUTS	8
5	13500	THRUST BEARING HOUSING	1
6	13600	THRUST BEARING	1

A A

UNLESS OTHERWISE SPECIFIED:

1. ALL DIMS. IN INCHES
2. TOLERANCES:
   X.XX = ±0.10
   ANGLES = ±1°
3. INSIDE TOOL RADIUS 0.5 MAX.
4. BREAK SHARP EDGES 0.5 MAX.
5. 1.6 √ FAO

MATERIAL
N/A

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JG	3/7/21
CHECKED	AC	3/7/21
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

F51 SUSTAINABLE ENERGY STORAGE

TITLE:

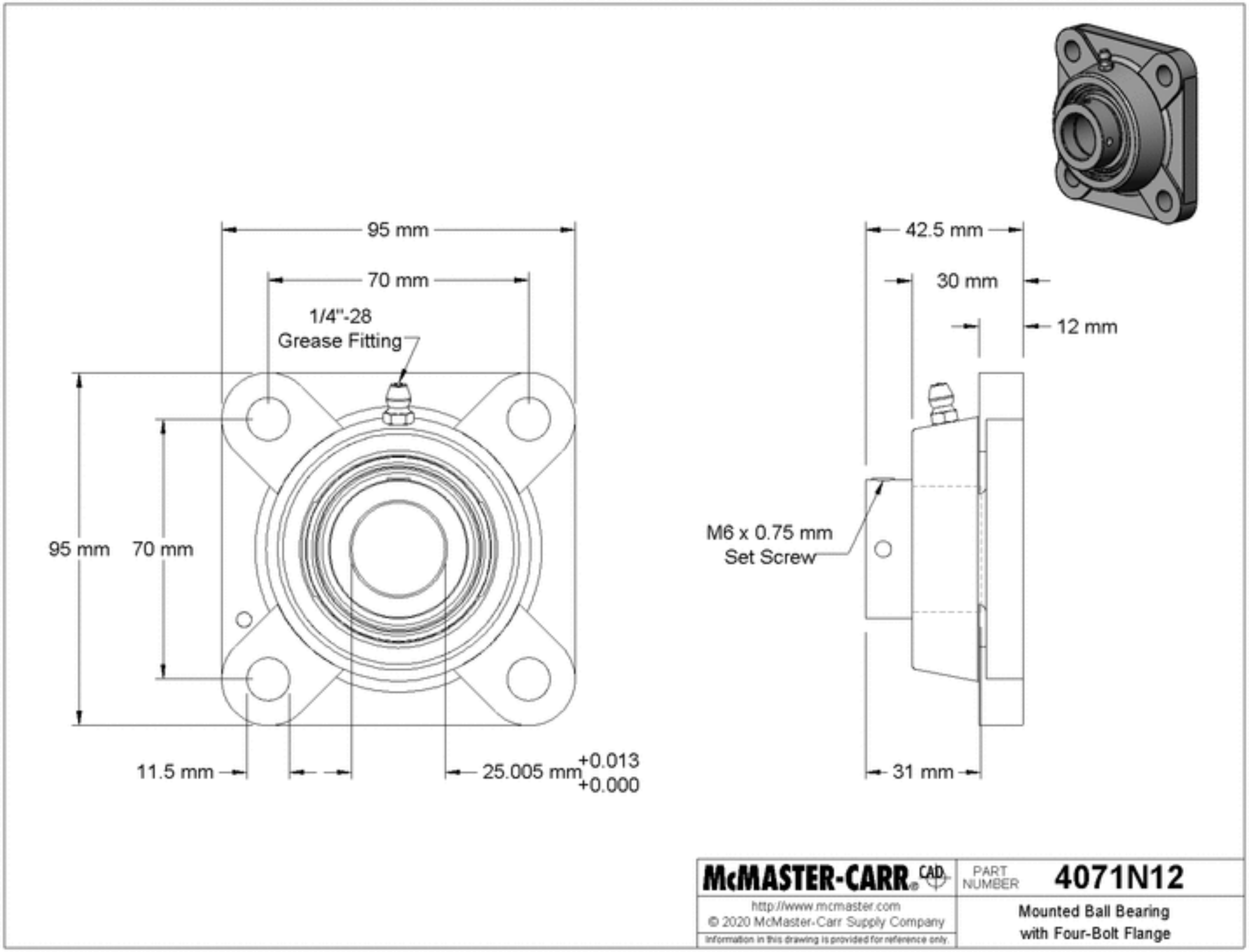
BEARING ASSEMBLY

SIZE	DWG. NO.	REV
A	13000E	A

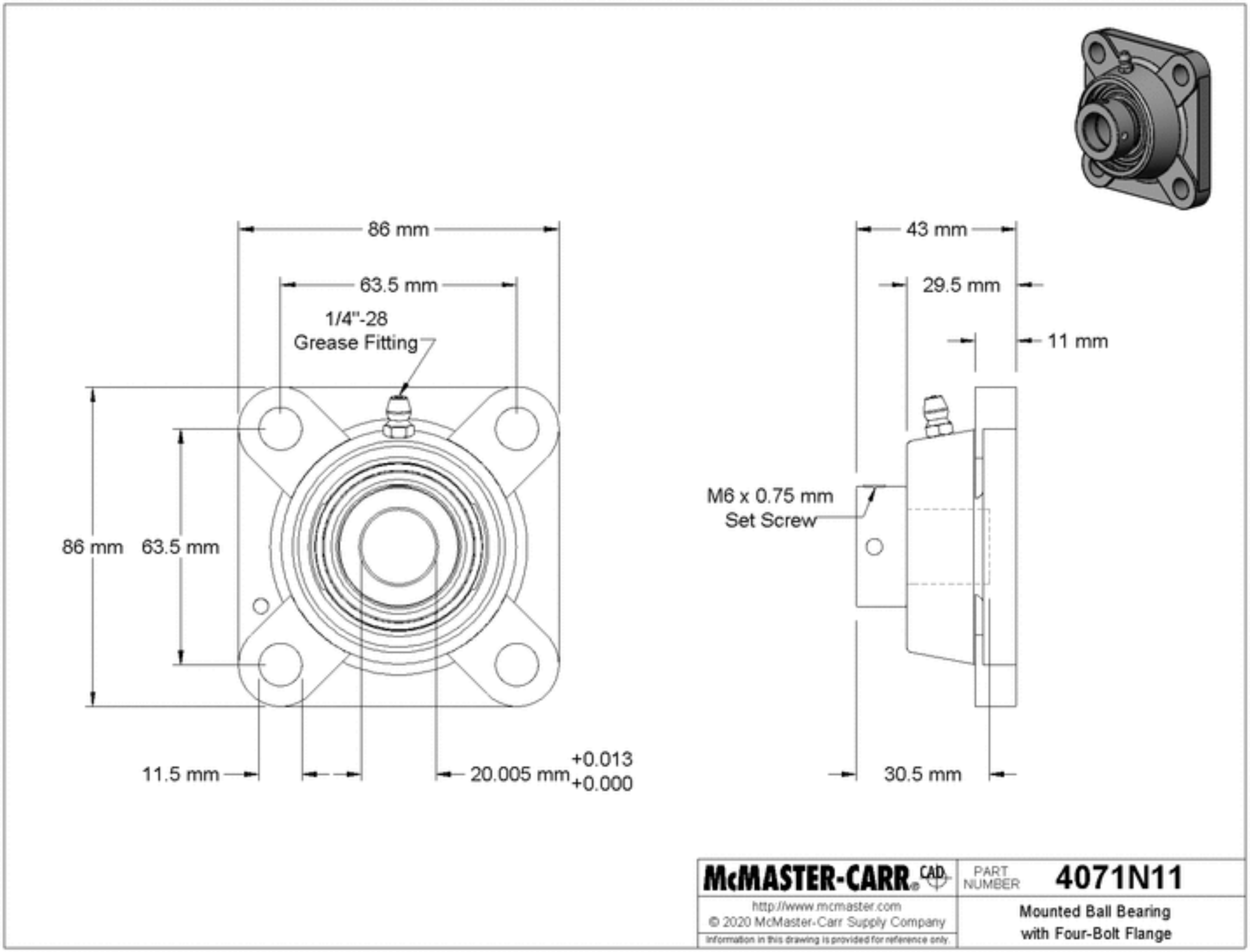
SCALE: 1:8 SHEET 1 OF 1

2 1

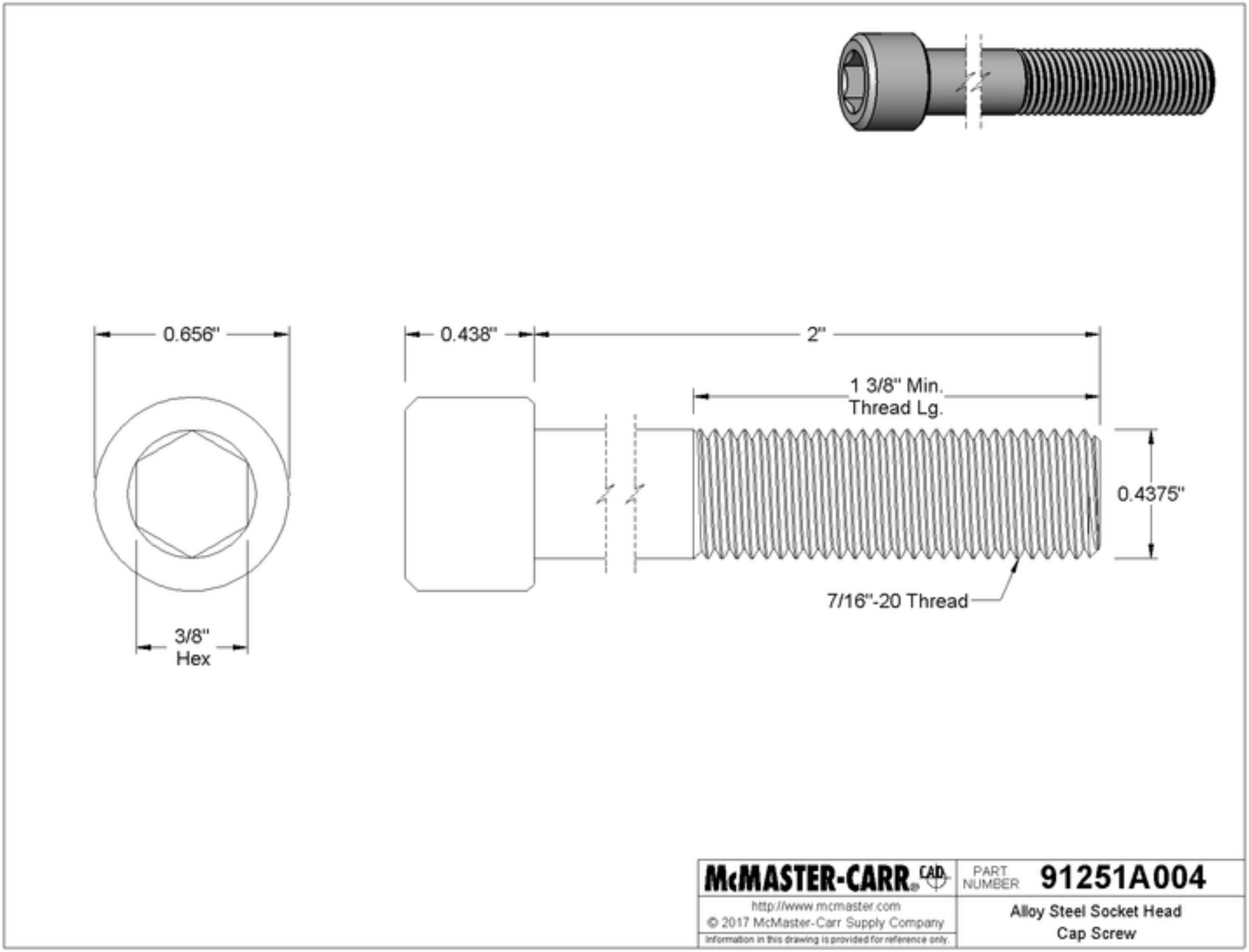
PART NUMBER: 13100



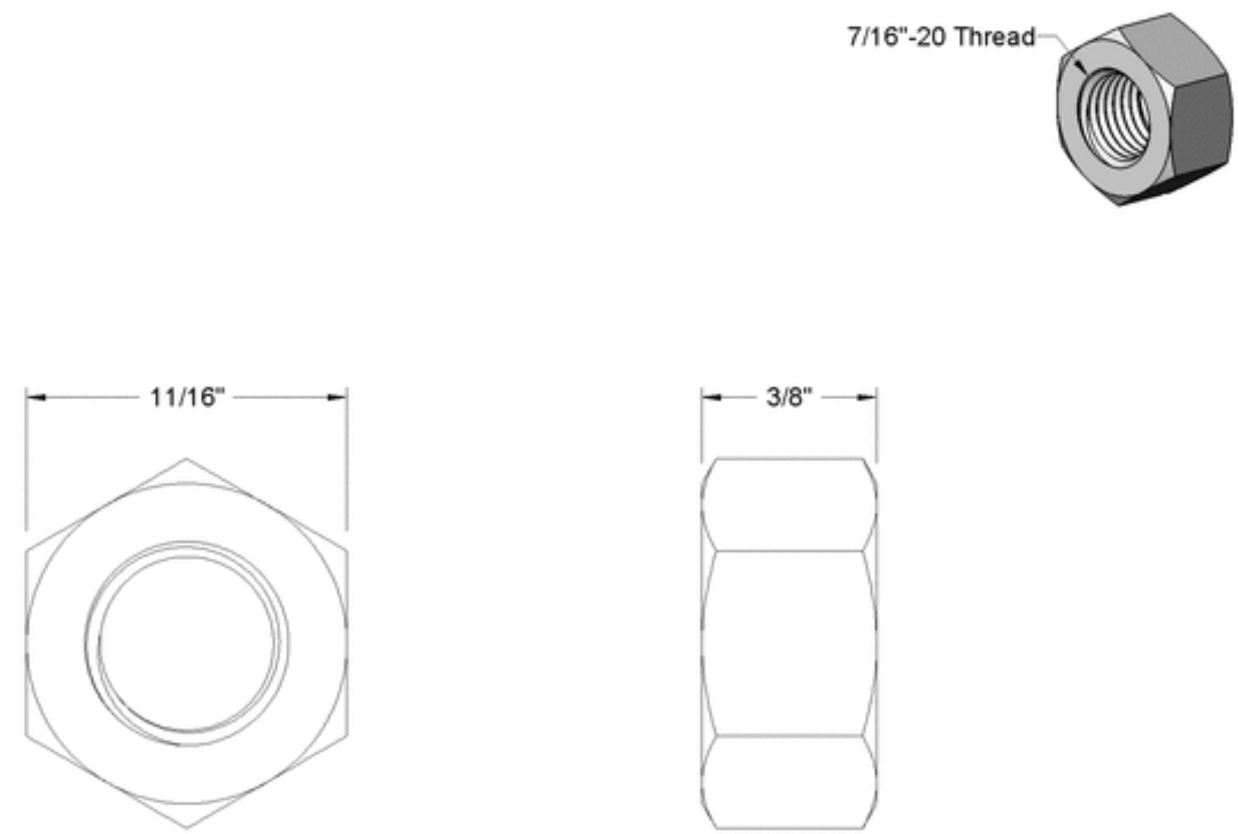
PART NUMBER: 13200



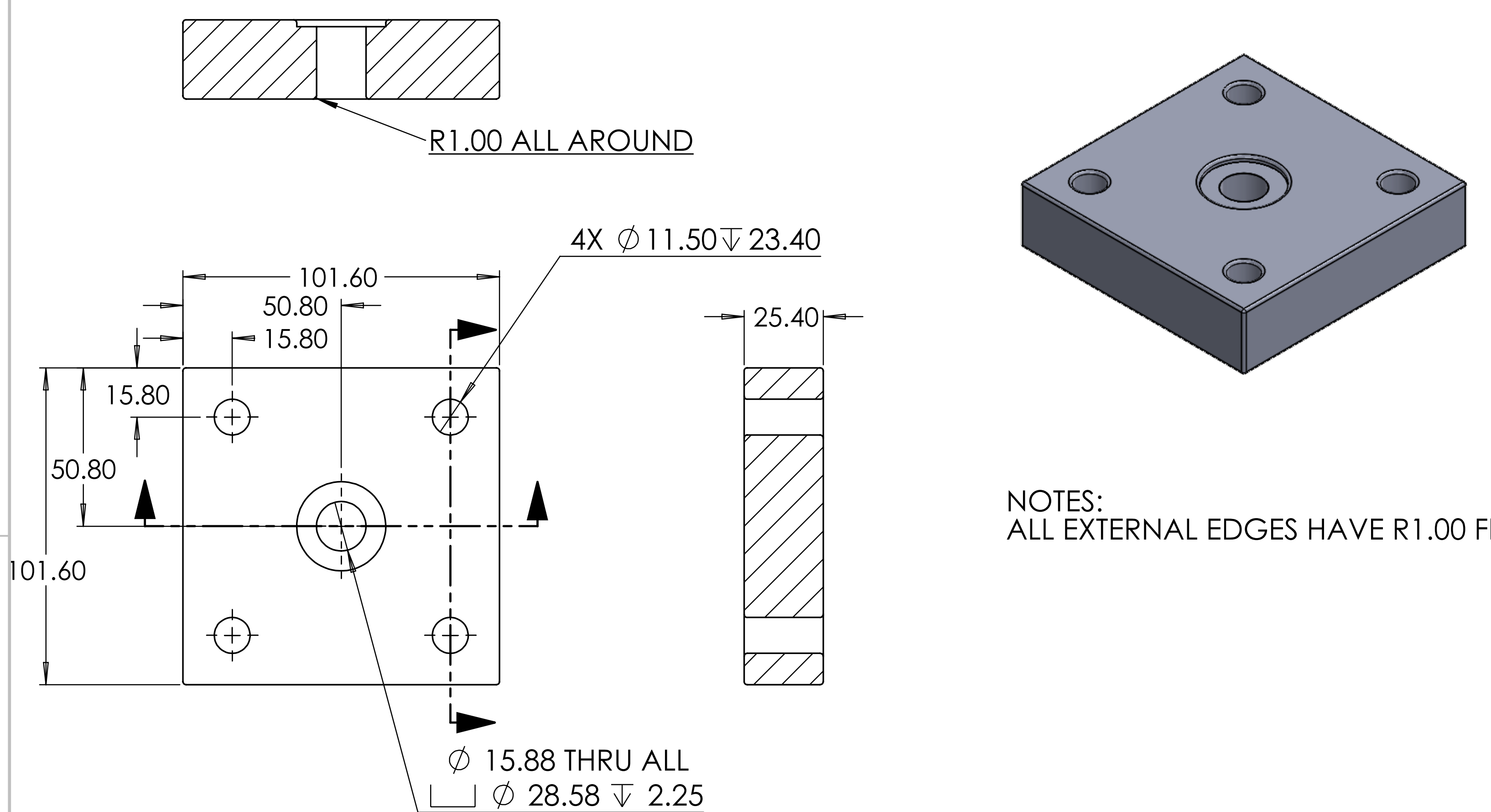
PART NUMBER: 13300



PART NUMBER: 13400



McMASTER-CARR. CAD	PART NUMBER	95479A215
http://www.mcmaster.com © 2015 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Hex Nut	



NOTES:
ALL EXTERNAL EDGES HAVE R1.00 FILLET

UNLESS OTHERWISE SPECIFIED:		NAME	DATE	F51 SUSTAINABLE ENERGY STORAGE
1. ALL DIMS. IN MILLIMETERS 2. TOLERANCES: X.XX = ±0.10 ANGLES = ±1° 3. INSIDE TOOL RADIUS 0.5 MAX. 4. BREAK SHARP EDGES 0.5 MAX. 5. 1.6 √ FAO	DRAWN	JRL	3/7/2021	TITLE:
	CHECKED	JSG	3/7/2021	THRUST BEARING HOUSING
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL LOW-CARBON STEEL	COMMENTS:			SIZE A · DWG. NO. 13500 · REV A
DO NOT SCALE DRAWING				SCALE: 1:2 · SHEET 1 OF 1

PART NUMBER: 13600

DESCRIPTION:

Needle Roller Thrust Bearing

Inner Bore: 5/8”

Outer Diameter: 1-1/8”

Thickness: 5/64”

Cage Material: Steel

Static Load Capacity: 30.38 kN

Bearing Material: Steel

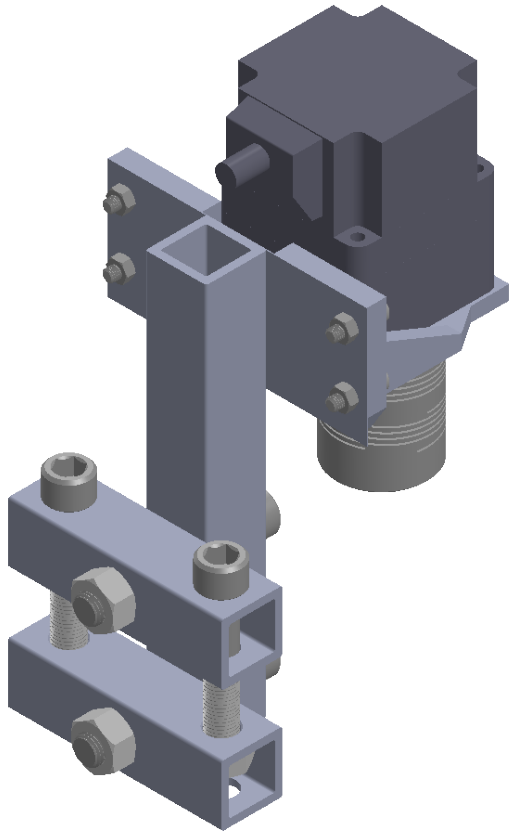
Dynamic Load Capacity: 9.79 kN

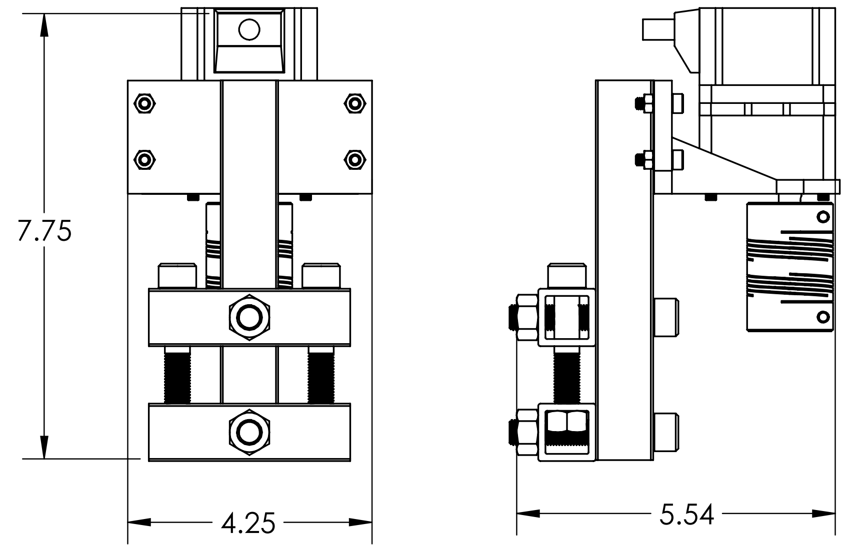
Maximum RPM: 15000 RPM

Thrust Bearing Type: Roller & Cage Assembly

2 1

B B

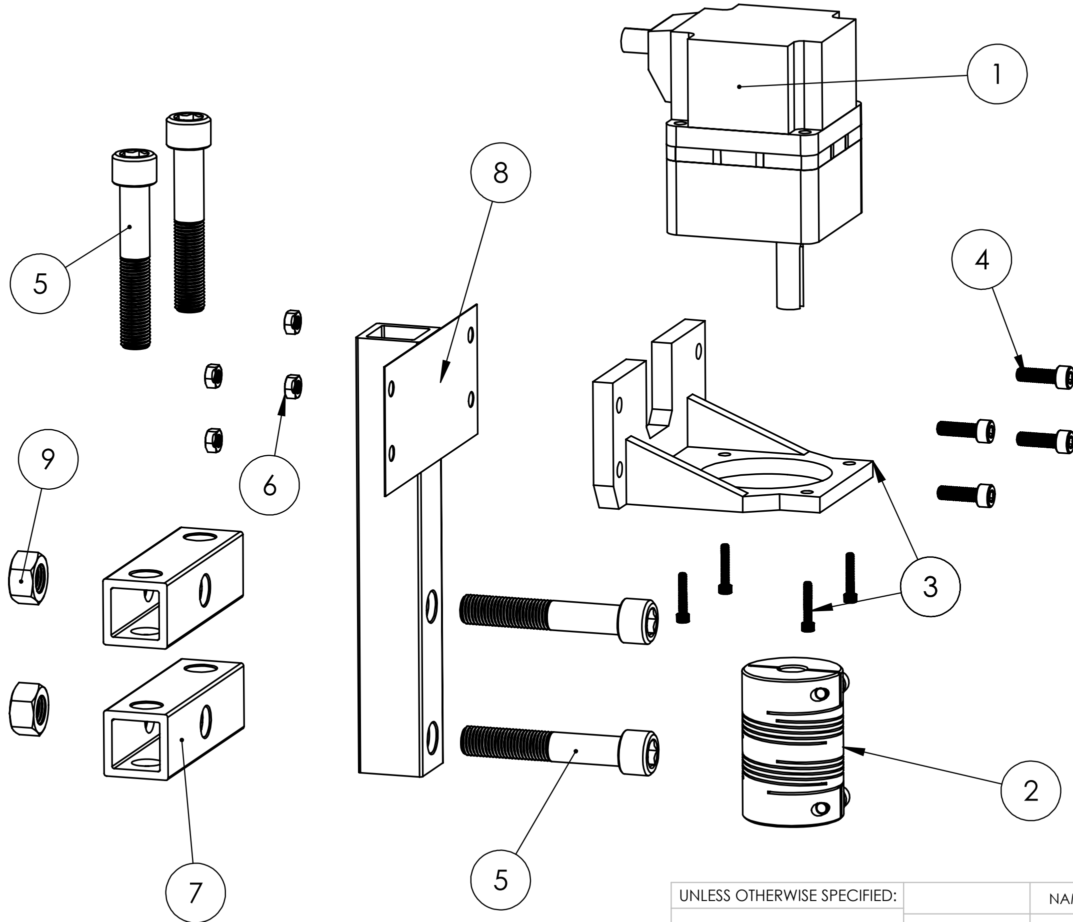




A A

UNLESS OTHERWISE SPECIFIED:		NAME	DATE	F51 SUSTAINABLE ENERGY STORAGE
1. ALL DIMS. IN INCHES 2. TOLERANCES: X.XX = ±0.10 ANGLES = ±1° 3. INSIDE TOOL RADIUS 0.5 MAX. 4. BREAK SHARP EDGES 0.5 MAX. 5. 1.6 FAO	DRAWN	JG	3/7/21	TITLE: MOTOR ASSEMBLY
	CHECKED	AC	3/7/21	
	ENG APPR.			
	MFG APPR.			
	Q.A.			
	COMMENTS:			SIZE A DWG. NO. 14000 REV A
MATERIAL N/A				SCALE: 1:8 SHEET 1 OF 1
DO NOT SCALE DRAWING				

2 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	14100	MOTOR	1
2	14200	SHAFT COUPLER	
3	14300	MOTOR MOUNTING BRACKET	1
4	14400	M5 BOLTS	4
5	14500	7/16" BOLTS	4
6	14600	M5 NUTS	4
7	14700	3.5" TUBE STOCK	2
8	14800	MOUNTING PLATE SUB-ASSYM	1
9	15100	7/16-20 NUT	4

UNLESS OTHERWISE SPECIFIED:

1. ALL DIMS. IN INCHES
2. TOLERANCES:
   X.XX = ±0.10
   ANGLES = ±1°
3. INSIDE TOOL RADIUS 0.5 MAX.
4. BREAK SHARP EDGES 0.5 MAX.
5. 1.6 √ FAO

MATERIAL
N/A

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JG	3/7/21
CHECKED	AC	3/7/21
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

F51 SUSTAINABLE ENERGY STORAGE

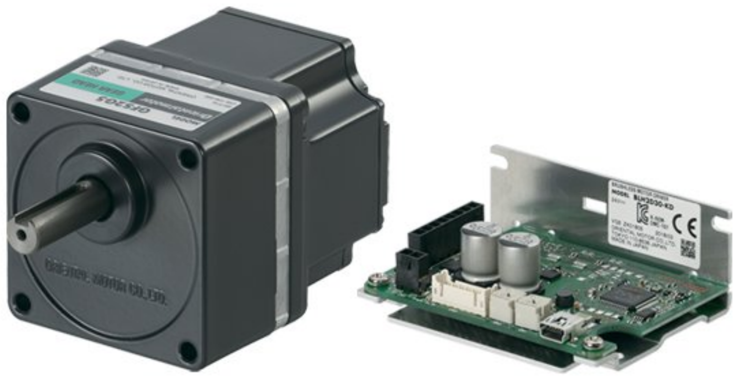
TITLE:

MOTOR ASSEMBLY

SIZE	DWG. NO.	REV
A	14000E	A

SCALE: 1:8 SHEET 1 OF 1

PART NUMBER: 14100

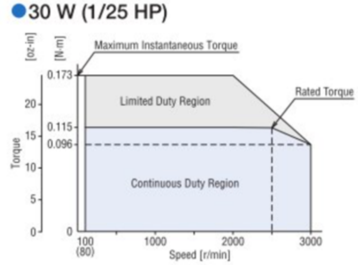


Motor Type	Brushless DC Motor
Motor Frame Size	60 mm
Output Power	30 W (1/25 HP)
Power Supply	24 VDC
Driver Type	Digital
Shaft/Gear Type	Parallel Shaft Gearhead
Gear Ratio (X:1)	5 :1
Output Shaft Diameter	10 mm
Rated Torque	0.52 N·m
Variable Speed Range (r/min)	16 ~ 600

Speed – Torque Characteristics

Continuous Duty Region: Continuous operation is possible in this region.
Limited Duty Region: This region is primarily used when accelerating.

● 30 W (1/25 HP)



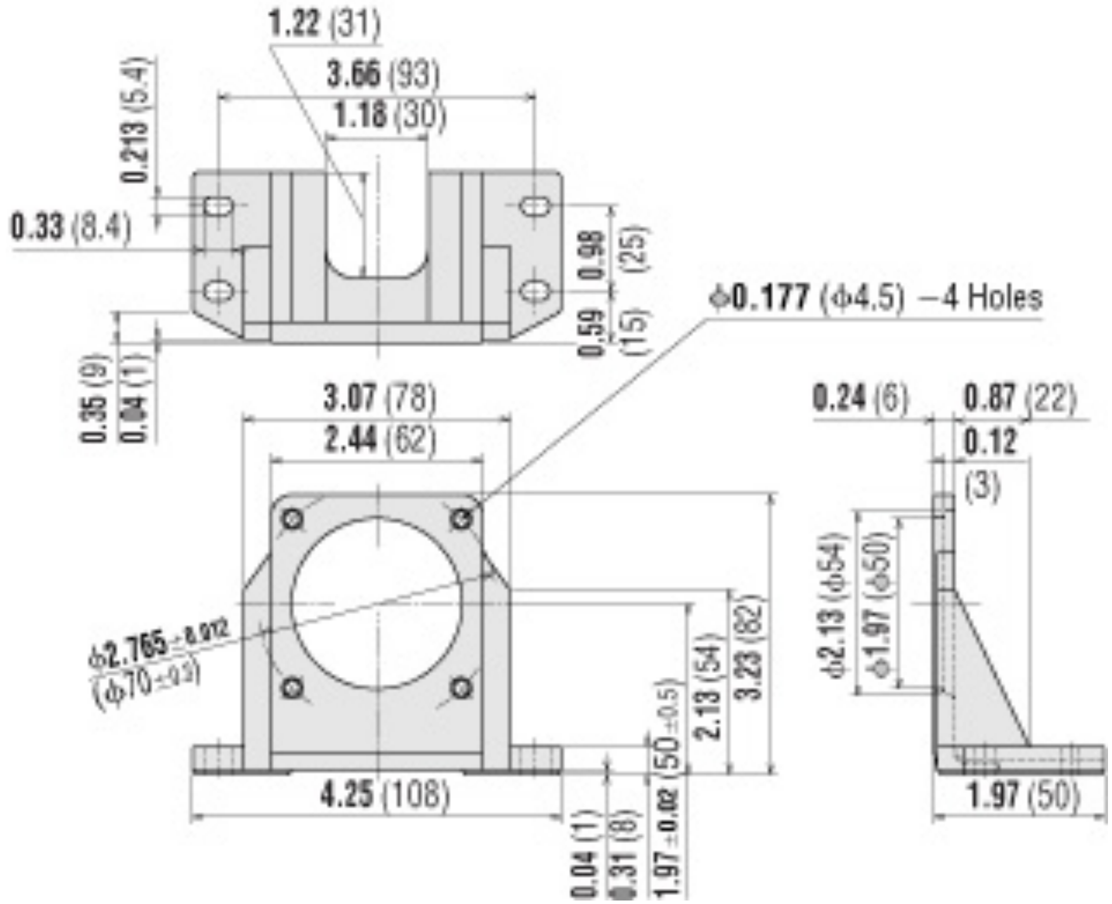
PART NUMBER: 14200

Outer Diameter	40 mm
Length	66 mm
Normal Torque	17 N·m
Shaft Hole Diameter d1	10 mm
Shaft Hole Diameter d2	20 mm
Inertia	42.29×10^{-6} kg·m²
Permissible End Play	1.20 mm
RoHS Compliant	Yes

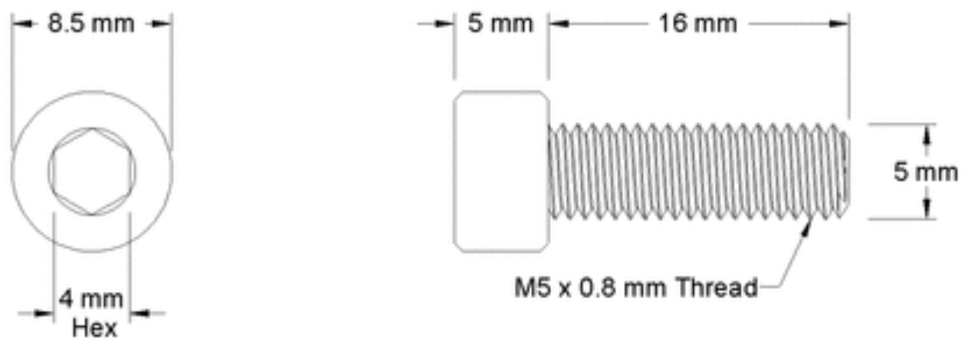
PART NUMBER: 14300

SOL2A-A

Weight: 4.2 oz. (120 g)



PART NUMBER: 14400



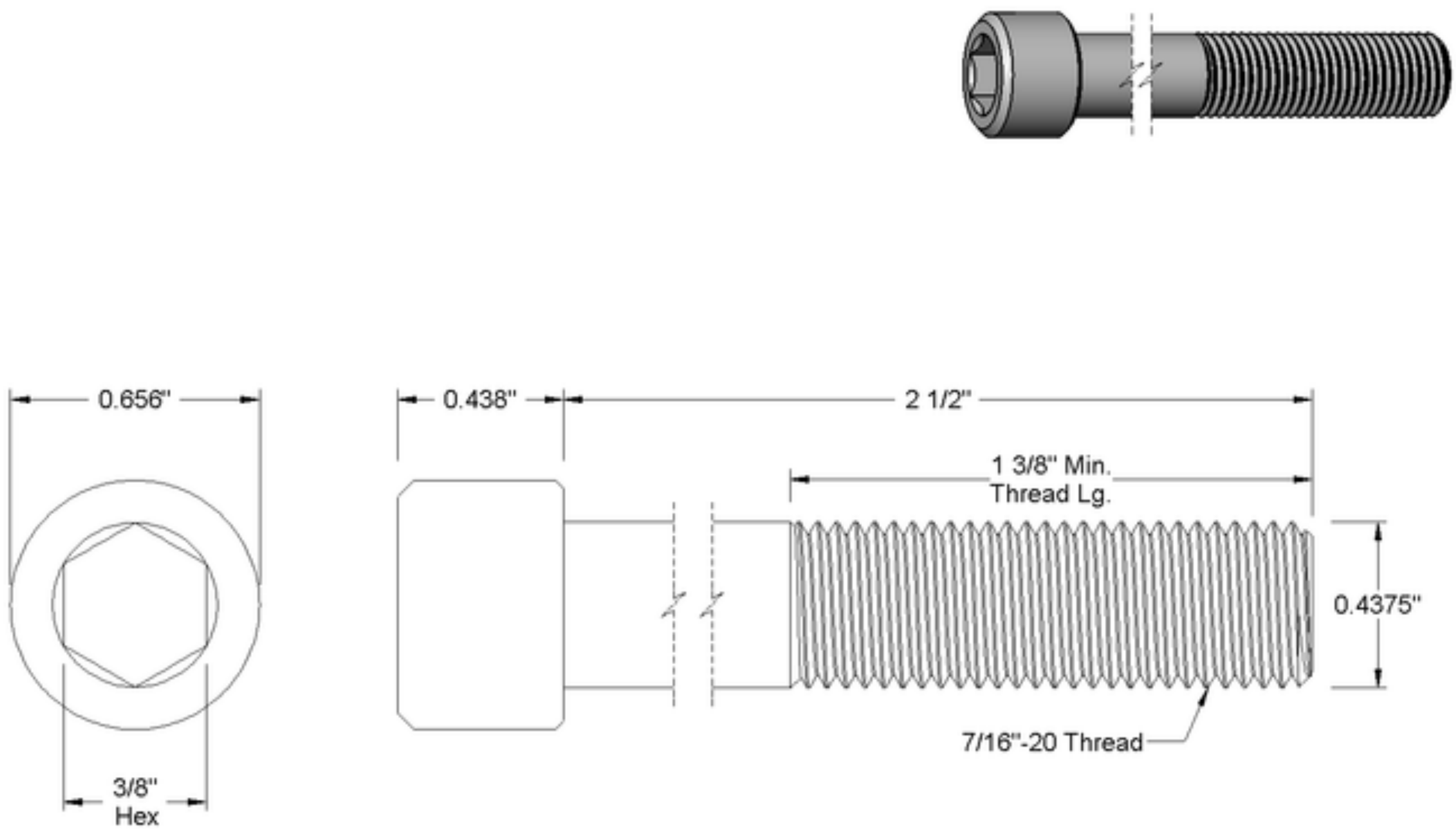
McMASTER-CARR® CAD

http://www.mcmaster.com

PART NUMBER 91292A126

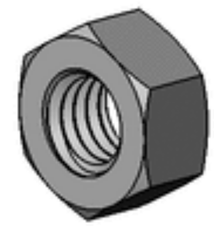
Stainless Steel
Socket Head Cap Screw

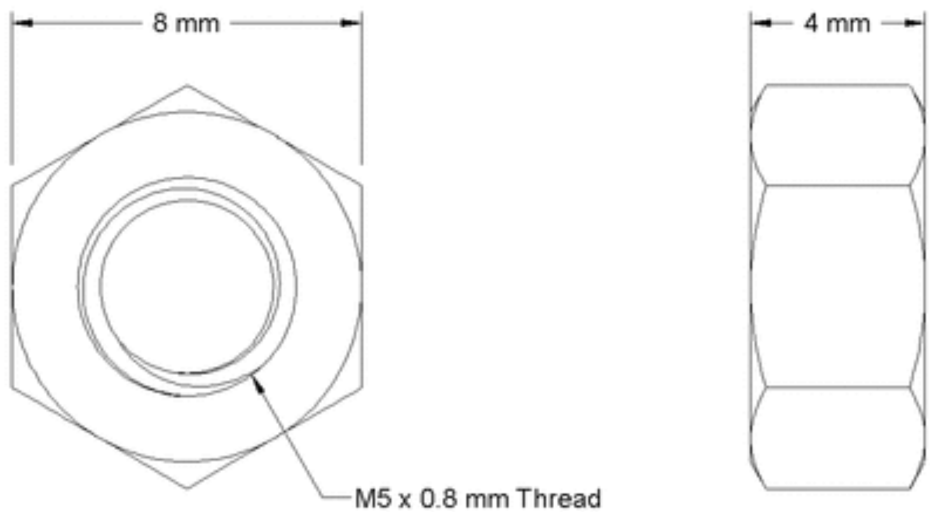
PART NUMBER: 14500



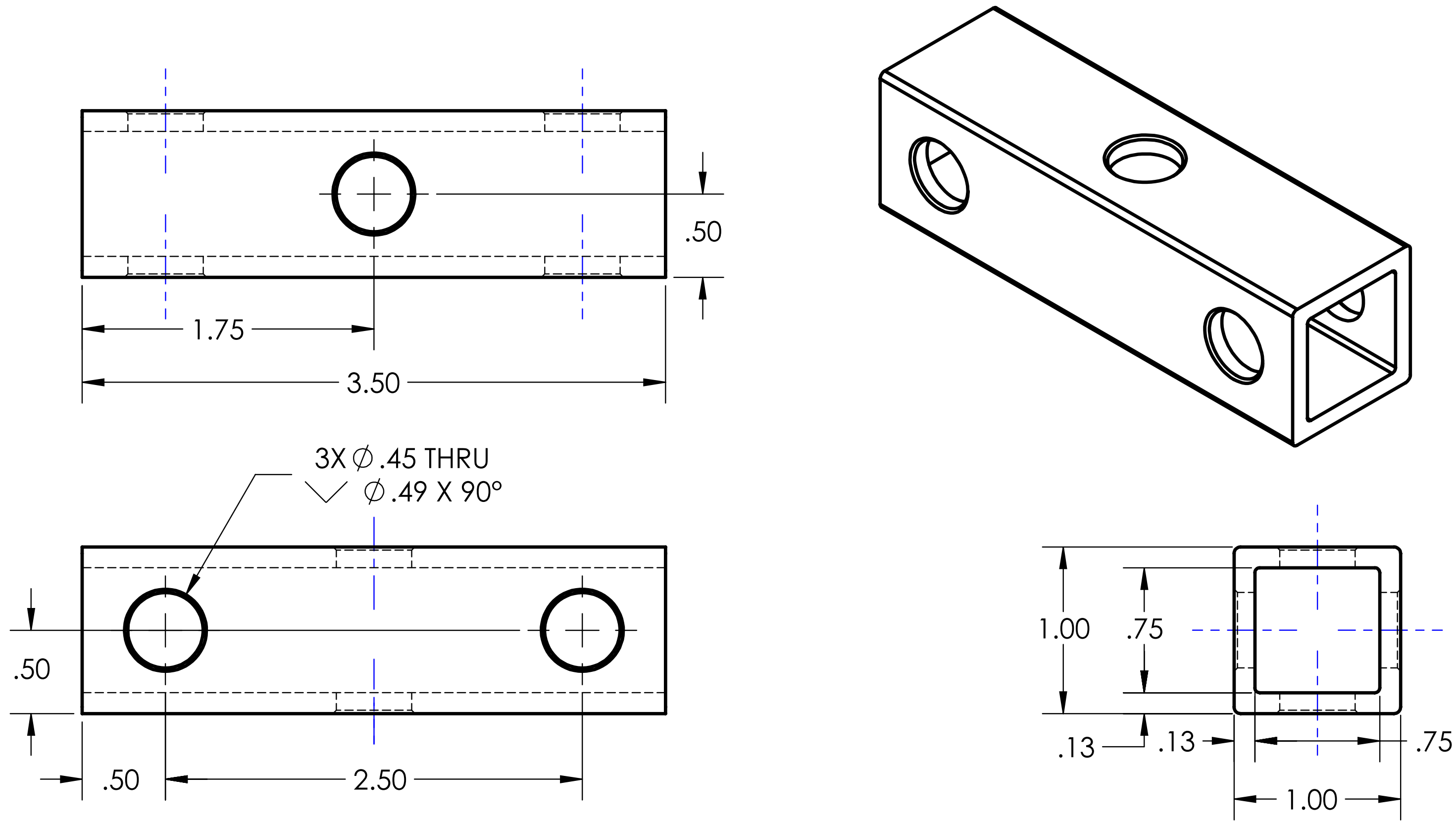
McMASTER-CARR® CAD	PART NUMBER 91251A005
http://www.mcmaster.com © 2017 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Alloy Steel Socket Head Cap Screw

PART NUMBER: 14600

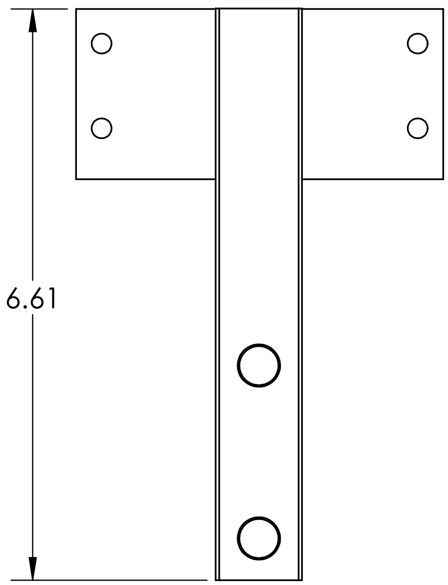


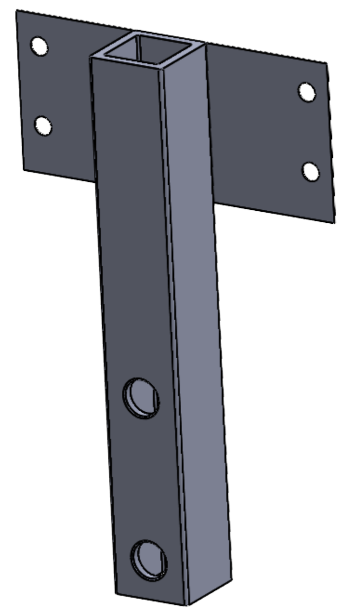


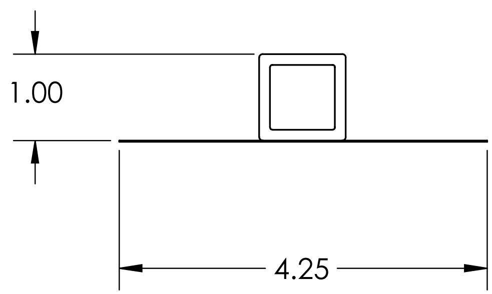
McMASTER-CARR® CAD	PART NUMBER	90592A095
http://www.mcmaster.com © 2020 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Metric Medium-Strength Steel Hex Nut - Class 8	



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	F51 SUSTAINABLE ENERGY STORAGE
1. ALL DIMS. IN INCHES 2. TOLERANCES: X.XX=±.01 X.XXX=±.005 ANGLES = ±1° 3. INSIDE TOOL RADIUS .02 MAX. 4. BREAK SHARP EDGES .01 MAX. 5. 63 √ FAO	DRAWN	AC	3/7	TITLE:
	CHECKED	JL	3/7	SQUARE TUBE STOCK (3.5")
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL 4130 STEEL	COMMENTS:			SIZE A · DWG. NO. 14700 · REV
DO NOT SCALE DRAWING				SCALE: 1:1 · SHEET 1 OF 1



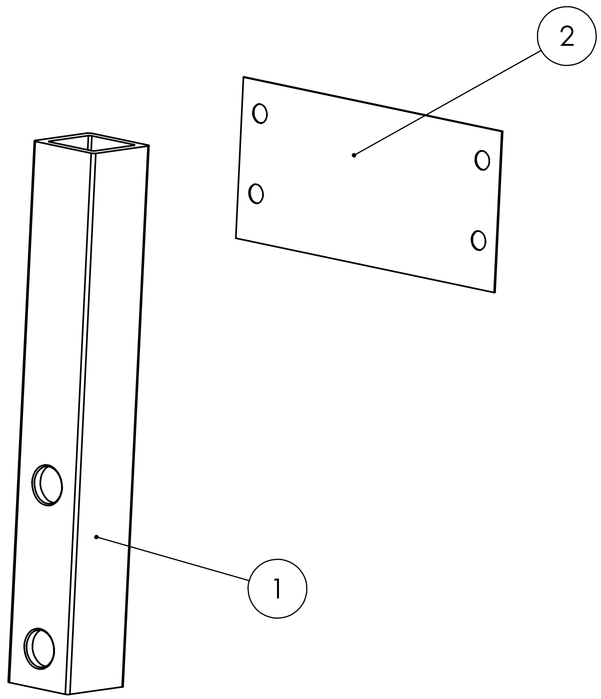




UNLESS OTHERWISE SPECIFIED:		NAME	DATE	F51 SUSTAINABLE ENERGY STORAGE
1. ALL DIMS. IN INCHES 2. TOLERANCES: X.XX = ±0.10 ANGLES = ±1° 3. INSIDE TOOL RADIUS 0.5 MAX. 4. BREAK SHARP EDGES 0.5 MAX. 5. 1.6 √ FAO	DRAWN	JG	3/7/21	TITLE:
	CHECKED	AC	3/7/21	MOUNTING PLATE SUB-ASSY
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL N/A	COMMENTS:			SIZE A · DWG. NO. 14800 · REV A
DO NOT SCALE DRAWING				SCALE: 1:8 · SHEET 1 OF 1

2 1

B



B

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	14810	6.6" TUBE STOCK	1
2	14820	MOUNTING PLATE	1

A A

UNLESS OTHERWISE SPECIFIED:

1. ALL DIMS. IN INCHES
2. TOLERANCES:
   X.XX = ±0.10
   ANGLES = ±1°
3. INSIDE TOOL RADIUS 0.5 MAX.
4. BREAK SHARP EDGES 0.5 MAX.
5. 1.6 √ FAO

MATERIAL
N/A

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JG	3/7/21
CHECKED	AC	3/7/21
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

F51 SUSTAINABLE ENERGY STORAGE

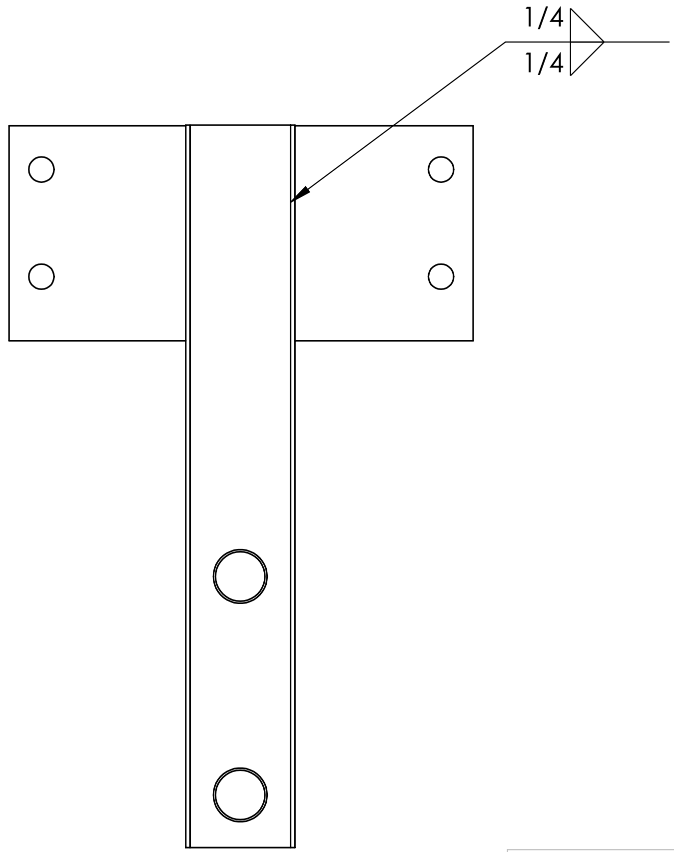
TITLE:

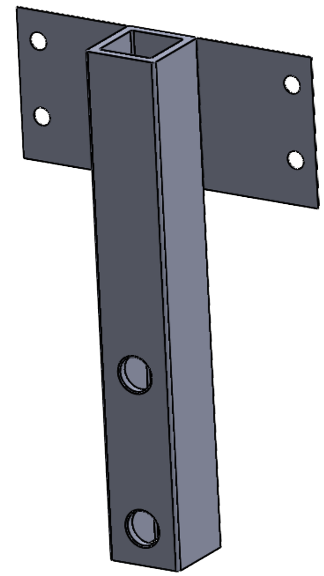
MOUNTING PLATE SUB-ASSY

SIZE	DWG. NO.	REV
A	14800E	A

SCALE: 1:4 SHEET 1 OF 1

2 1





UNLESS OTHERWISE SPECIFIED:

1. ALL DIMS. IN INCHES
2. TOLERANCES:
   X.XX = ±0.10
   ANGLES = ±1°
3. INSIDE TOOL RADIUS 0.5 MAX.
4. BREAK SHARP EDGES 0.5 MAX.
5. 1.6 √ FAO

MATERIAL
N/A

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JG	3/7/21
CHECKED	AC	3/7/21
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

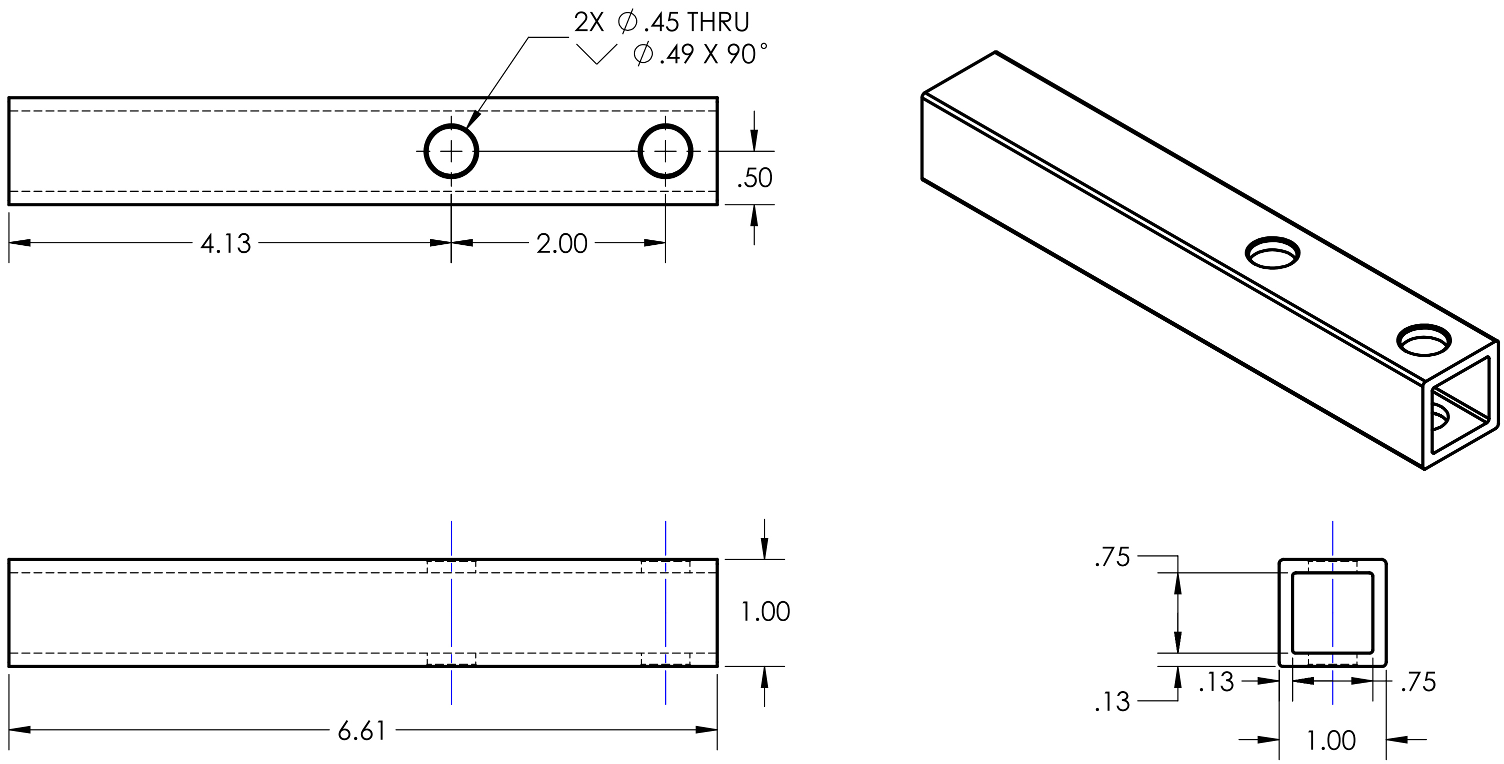
F51 SUSTAINABLE ENERGY STORAGE

TITLE:

MOUNTING PLATE SUB-ASSY

SIZE	DWG. NO.	REV
A	14800W	A

SCALE: 1:8 SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

1. ALL DIMS. IN INCHES
2. TOLERANCES:
   X.XX = ±.01
   X.XXX = ±.005
   ANGLES = ±1°
3. INSIDE TOOL RADIUS .02 MAX.
4. BREAK SHARP EDGES .01 MAX.
5. 63 √ FAO

MATERIAL
4130 ALLOY STEEL

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	AC	3/7
CHECKED	JL	3/7
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

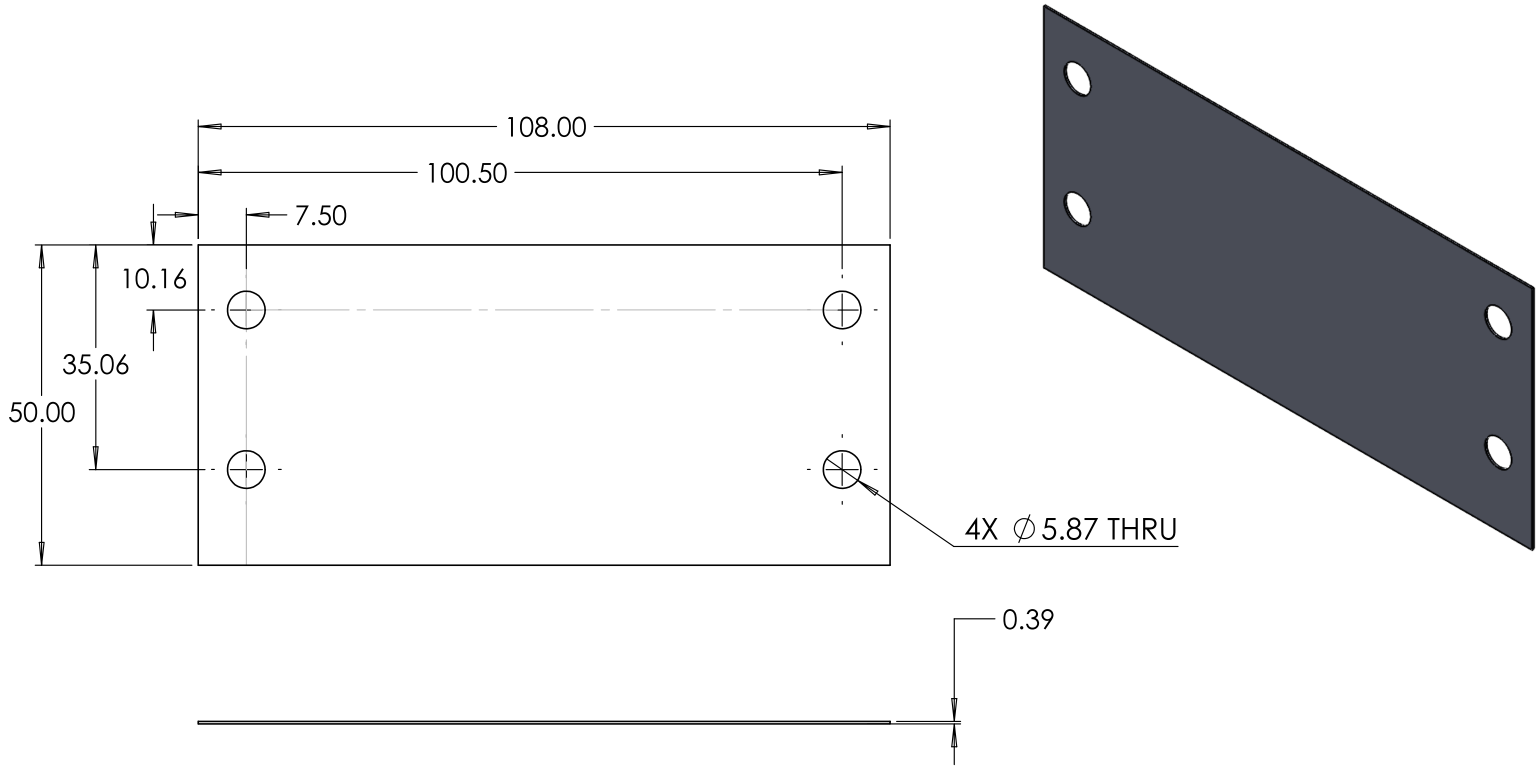
F51 SUSTAINABLE ENERGY STORAGE

TITLE:

SQUARE TUBE STOCK (6.6")

SIZE **A** DWG. NO. 14810 REV

SCALE: 1:1.5 SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

1. ALL DIMS. IN MILLIMETERS
2. TOLERANCES:
   X.XX = ±0.10
   ANGLES = ±1°
3. INSIDE TOOL RADIUS 0.5 MAX.
4. BREAK SHARP EDGES 0.5 MAX.
5. 1.6 √ FAO

MATERIAL
LOW-CARBON STEEL

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JRL	3/8/2021
CHECKED	JSG	3/8/2021
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

F51 SUSTAINABLE ENERGY STORAGE

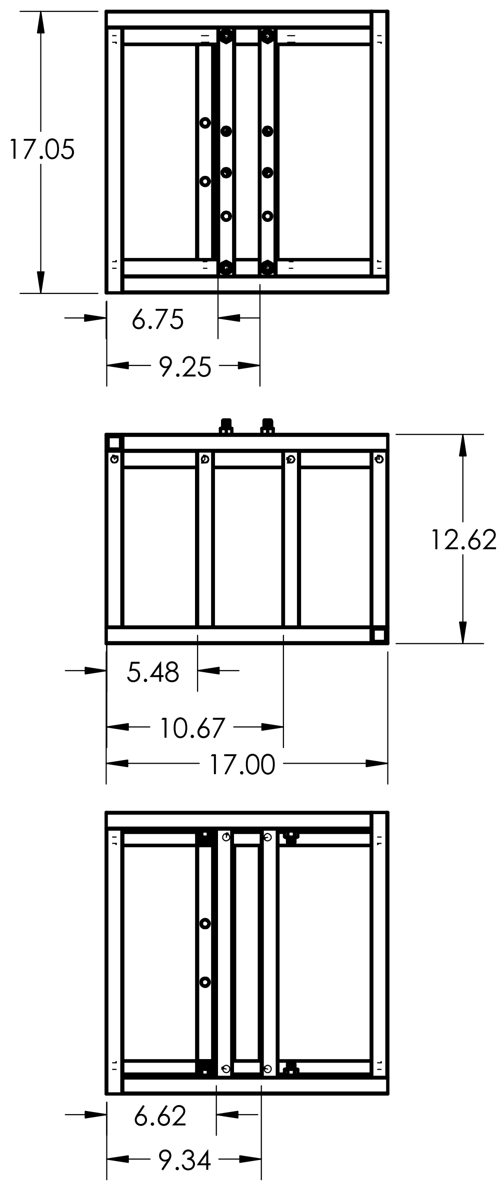
TITLE:

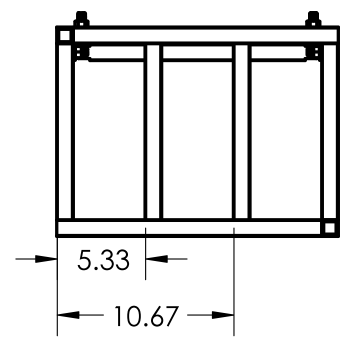
MOTOR MOUNTING PLATE

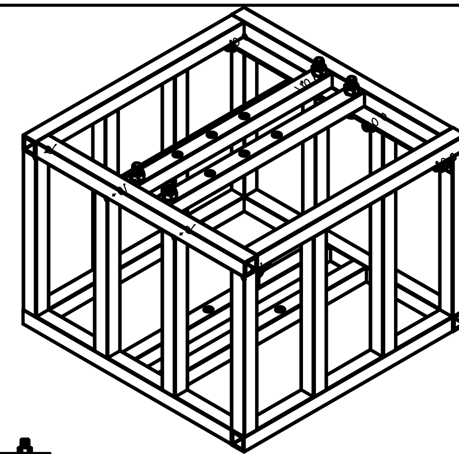
SIZE	DWG. NO.	REV
A	14820	A

SCALE: 1:1

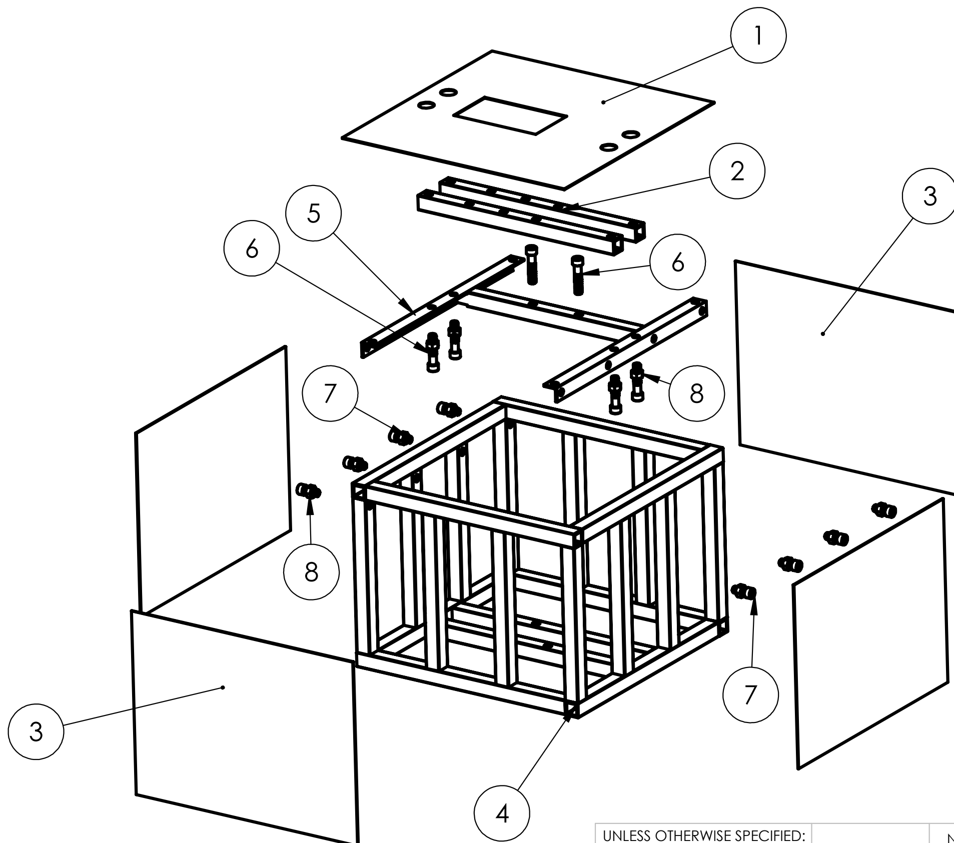
SHEET 1 OF 1







UNLESS OTHERWISE SPECIFIED:		NAME	DATE	F51 SUSTAINABLE ENERGY STORAGE
1. ALL DIMS. IN INCHES 2. TOLERANCES: X.XX = ±.01 X.XXX = ±.005 ANGLES = ±1° 3. INSIDE TOOL RADIUS .02 MAX. 4. BREAK SHARP EDGES .01 MAX. 5. 63 √ FAO	DRAWN	AC	3/8	TITLE:
	CHECKED	JL	3/8	CHASSIS ASSEMBLY
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL N/A	COMMENTS: STEEL PLATE SIDING WAS EXCLUDED FROM THIS ASSEMBLY DRAWING SO DIMS OF SUPPORTING BARS COULD BE SEEN. STEEL PLATES ARE STILL INCLUDED IN THE EXPLODED VIEW.			SIZE A · DWG. NO. 15000 · REV
DO NOT SCALE DRAWING				SCALE: 1:10 · SHEET 1 OF 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	15700B	TOP STEEL PLATE	1
2	15400	SQUARE TUBE STOCK (15")	2
3	15700A	SIDE STEEL PLATE	4
4	15200	WELDED FRAME SUB	1
5	15300	WELDED H SUB-ASSY	1
6	14500	7/16" X 20, 2.5" BOLT	6
7	15500	7/16" X 20, 1" BOLT	8
8	15100	7/16" X 20 NUT	12

UNLESS OTHERWISE SPECIFIED:

1. ALL DIMS. IN INCHES
2. TOLERANCES:
   X.XX = ±.01
   X.XXX = ±.005
   ANGLES = ±1°
3. INSIDE TOOL RADIUS .02 MAX.
4. BREAK SHARP EDGES .01 MAX.
5. 63 √ FAO

MATERIAL
N/A

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JG	3/8
CHECKED	AC	3/8
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

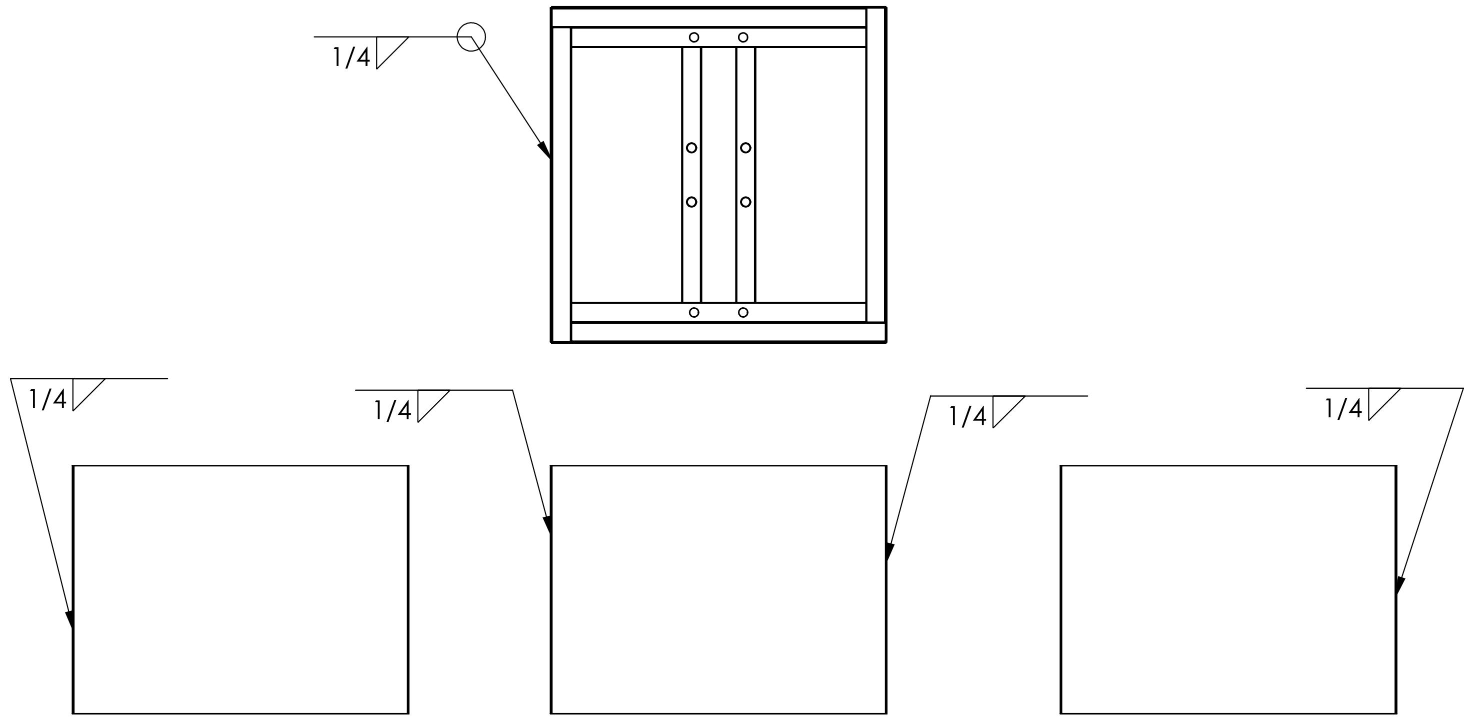
F51 SUSTAINABLE ENERGY STORAGE

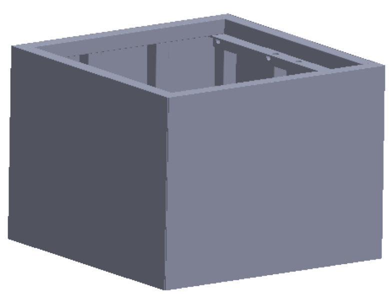
TITLE:

CHASSIS ASSEMBLY

SIZE A DWG. NO. 15000E REV

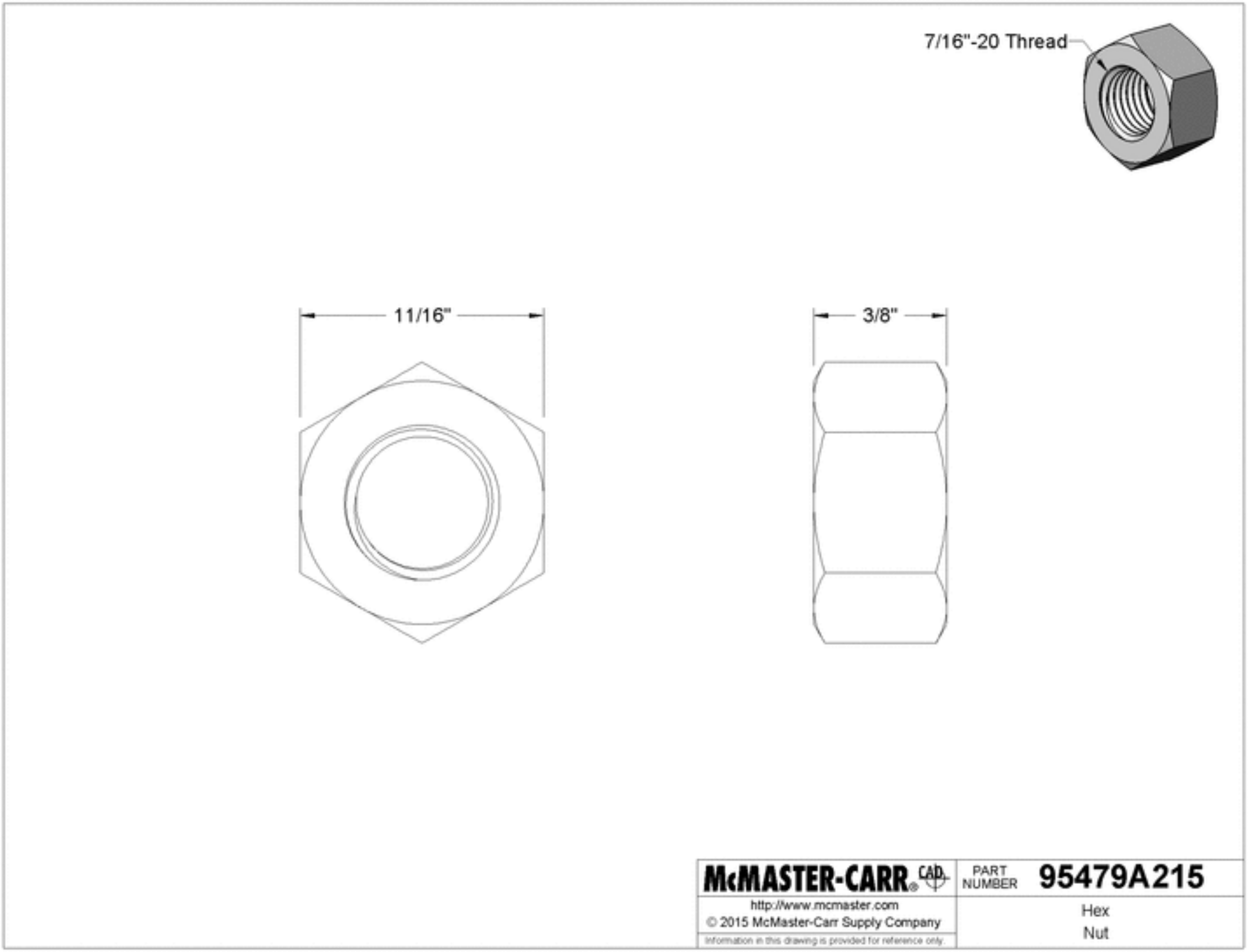
SCALE: 1:10 SHEET 1 OF 1

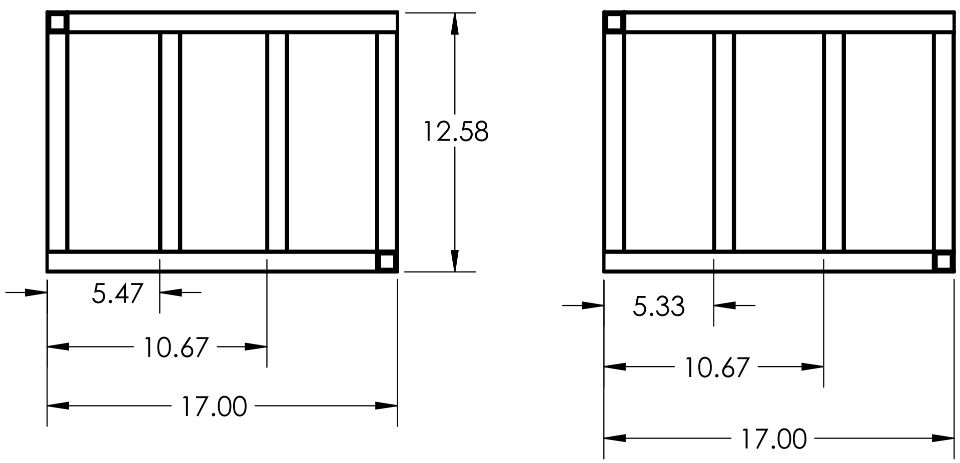


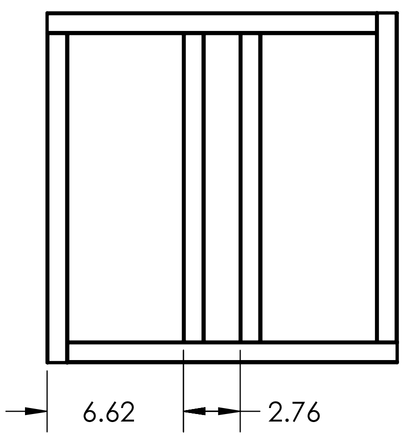


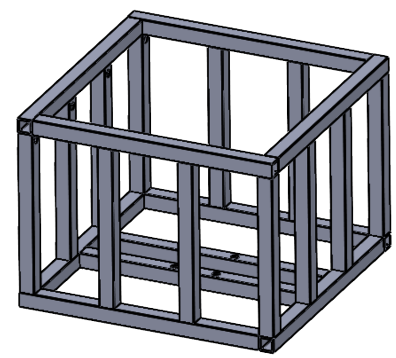
UNLESS OTHERWISE SPECIFIED:		NAME	DATE	F51 SUSTAINABLE ENERGY STORAGE
1. ALL DIMS. IN INCHES 2. TOLERANCES: X.XX = ±0.10 ANGLES = ±1° 3. INSIDE TOOL RADIUS 0.5 MAX. 4. BREAK SHARP EDGES 0.5 MAX. 5. 1.6 √ FAO	DRAWN	JG	3/7/21	TITLE:
	CHECKED	AC	3/7/21	CHASSIS ASSEMBLY
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL N/A	COMMENTS:			SIZE A · DWG. NO. 15000W · REV A
DO NOT SCALE DRAWING				SCALE: 1:8 · SHEET 1 OF 1

PART NUMBER: 15100

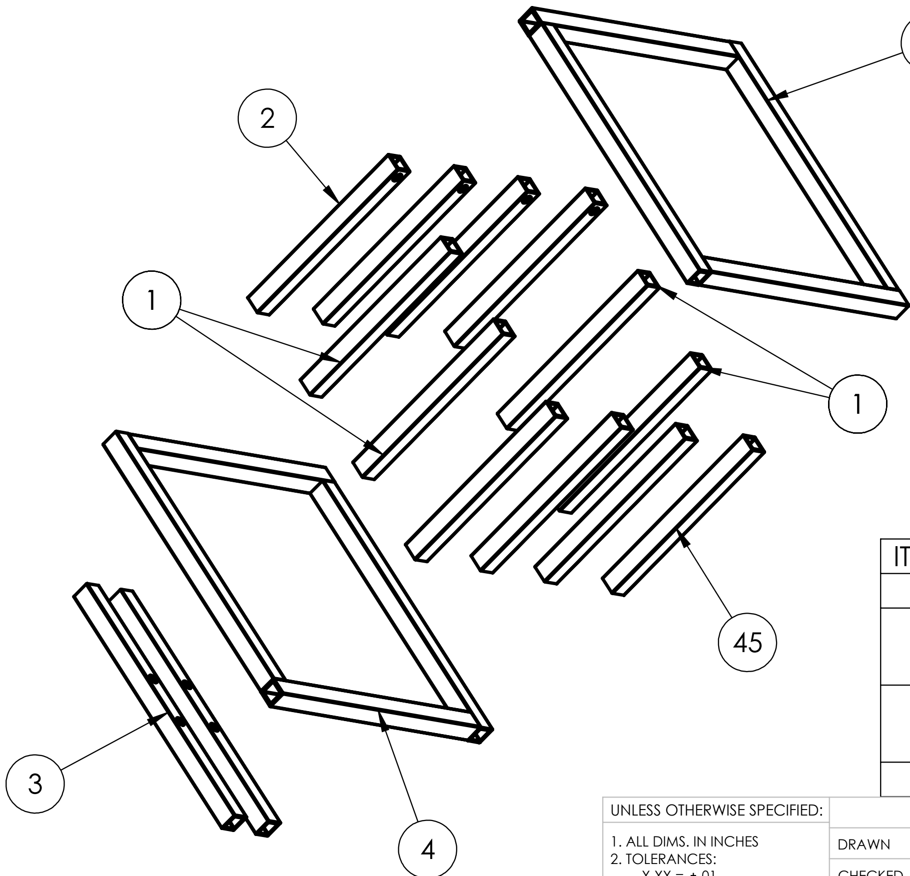


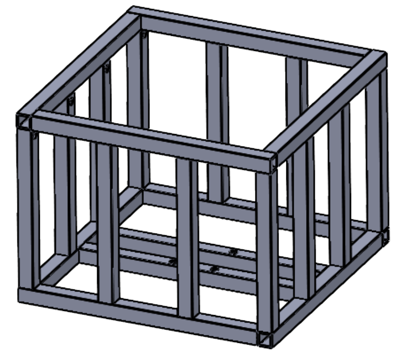






UNLESS OTHERWISE SPECIFIED:		NAME	DATE	F51 SUSTAINABLE ENERGY STORAGE
1. ALL DIMS. IN INCHES 2. TOLERANCES: X.XX = ±.01 X.XXX = ±.005 ANGLES = ±1° 3. INSIDE TOOL RADIUS .02 MAX. 4. BREAK SHARP EDGES .01 MAX. 5. 63 √ FAO	DRAWN	JG	3/8	
	CHECKED	AC	3/8	TITLE: WELDED FRAME SUB-ASSYM
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL N/A	COMMENTS:			SIZE A — DWG. NO. 15200 — REV
DO NOT SCALE DRAWING				SCALE: 1:10 — SHEET 1 OF 1





ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	15210	10.5" STOCK	4
2	15220	10.5" W/ HOLES STOCK	8
3	15230	15" LOWER STOCK	2
4	15240	16" STOCK	8

UNLESS OTHERWISE SPECIFIED:

1. ALL DIMS. IN INCHES
2. TOLERANCES:
   X.XX = ±.01
   X.XXX = ±.005
   ANGLES = ±1°
3. INSIDE TOOL RADIUS .02 MAX.
4. BREAK SHARP EDGES .01 MAX.
5. 63 √ FAO

MATERIAL
N/A

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JG	3/8
CHECKED	AC	3/8
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

F51 SUSTAINABLE ENERGY STORAGE

TITLE:

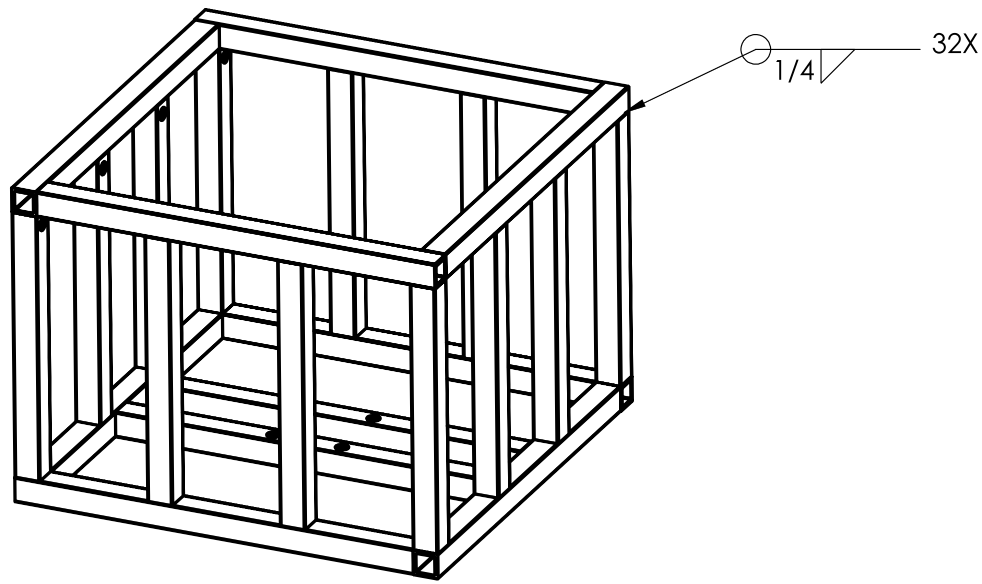
WELDED FRAME SUB-ASSYM

SIZE	DWG. NO.	REV
A	15200E	

SCALE: 1:10 SHEET 1 OF 1

2 1

B



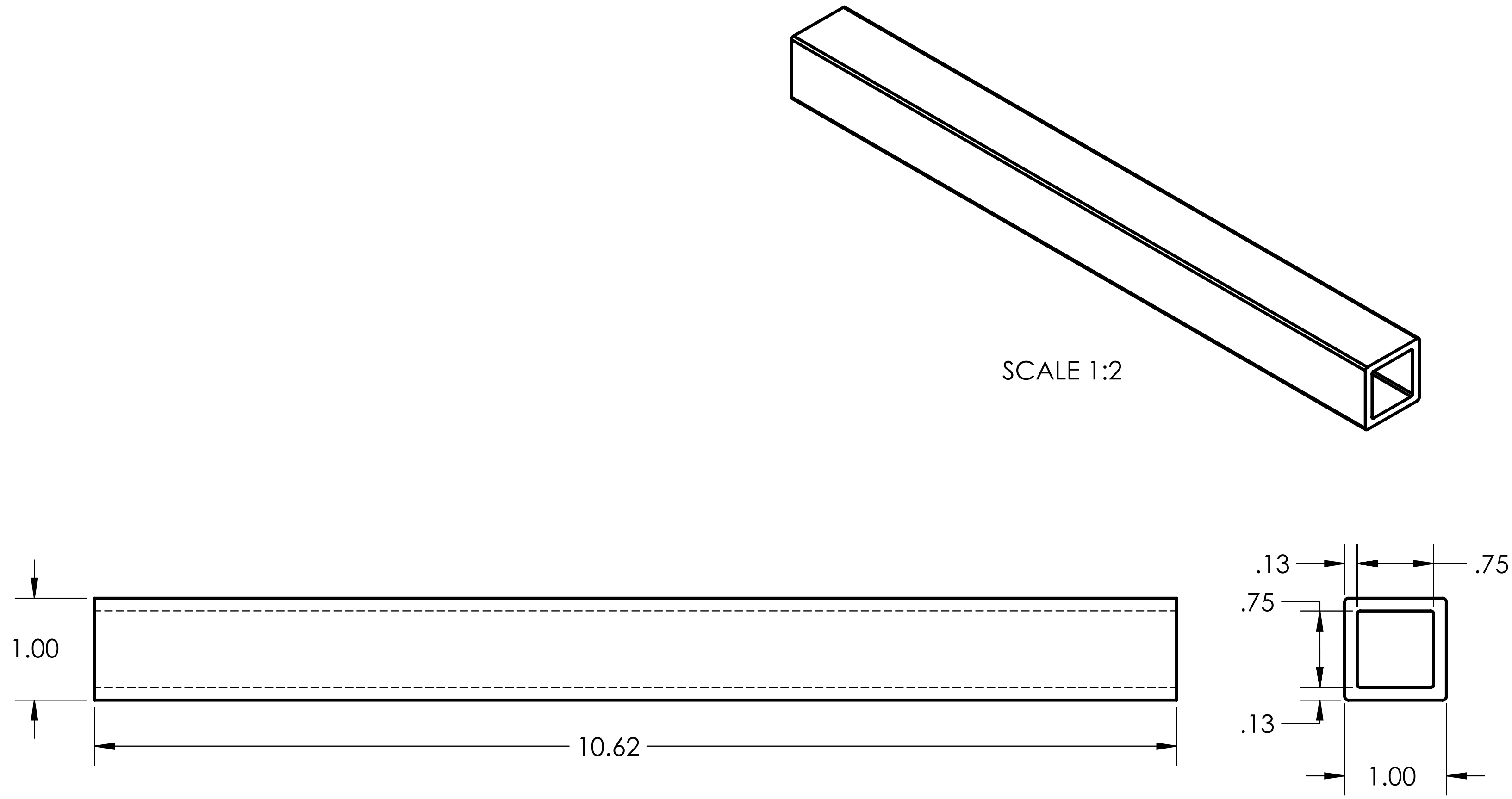
B

A

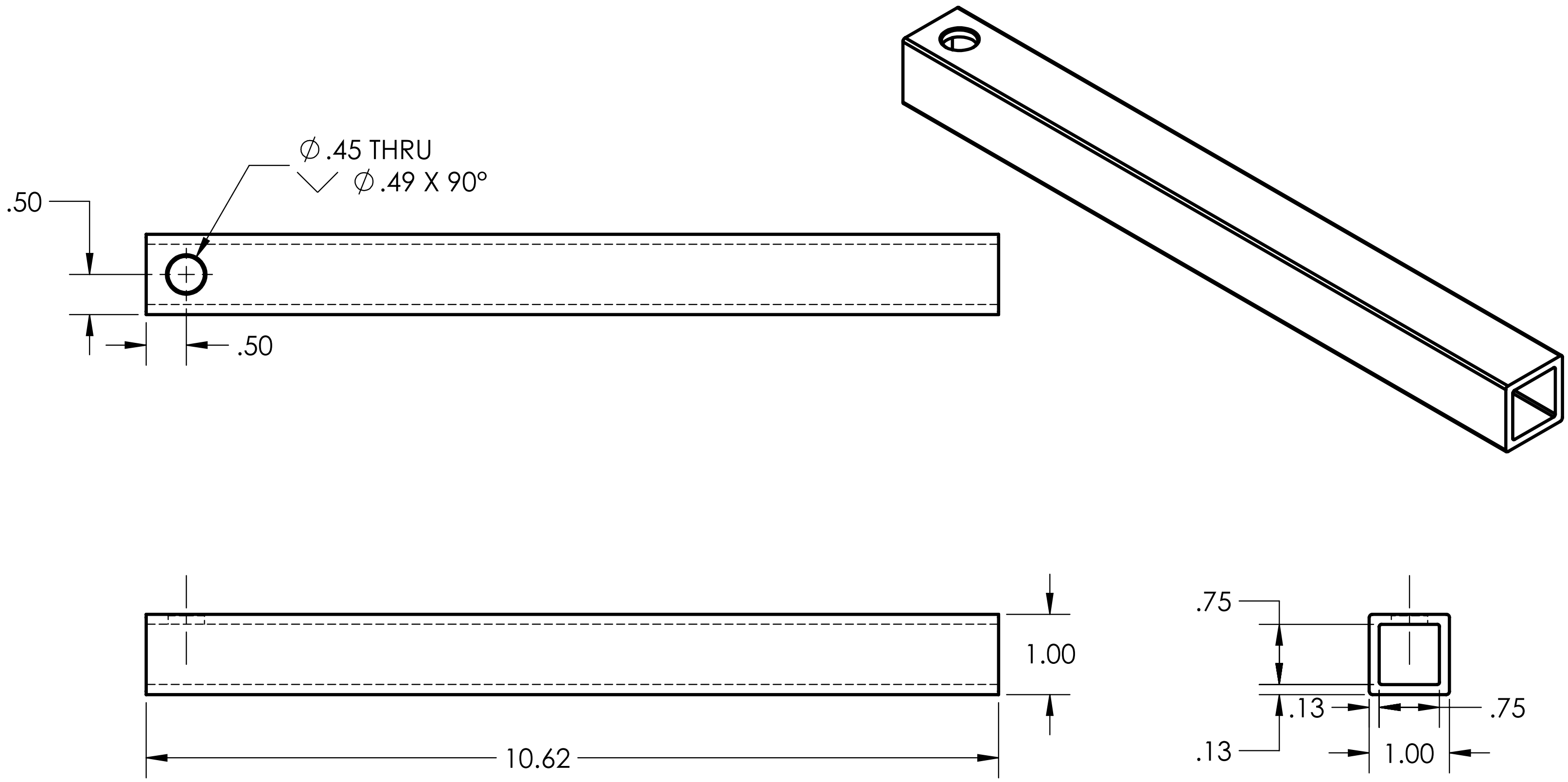
UNLESS OTHERWISE SPECIFIED:		NAME	DATE	F51 SUSTAINABLE ENERGY STORAGE
1. ALL DIMS. IN INCHES 2. TOLERANCES: X.XX = ±.01 X.XXX = ±.005 ANGLES = ±1° 3. INSIDE TOOL RADIUS .02 MAX. 4. BREAK SHARP EDGES .01 MAX. 5. 63 √ FAO	DRAWN	JG	3/8	
	CHECKED	AC	3/8	TITLE: WELDED FRAME SUB-ASSYM
	ENG APPR.			
	MFG APPR.			
	Q.A.			
	COMMENTS:			SIZE A — DWG. NO. 15200W — REV
MATERIAL N/A				
DO NOT SCALE DRAWING				SCALE: 1:10 — SHEET 1 OF 1

A

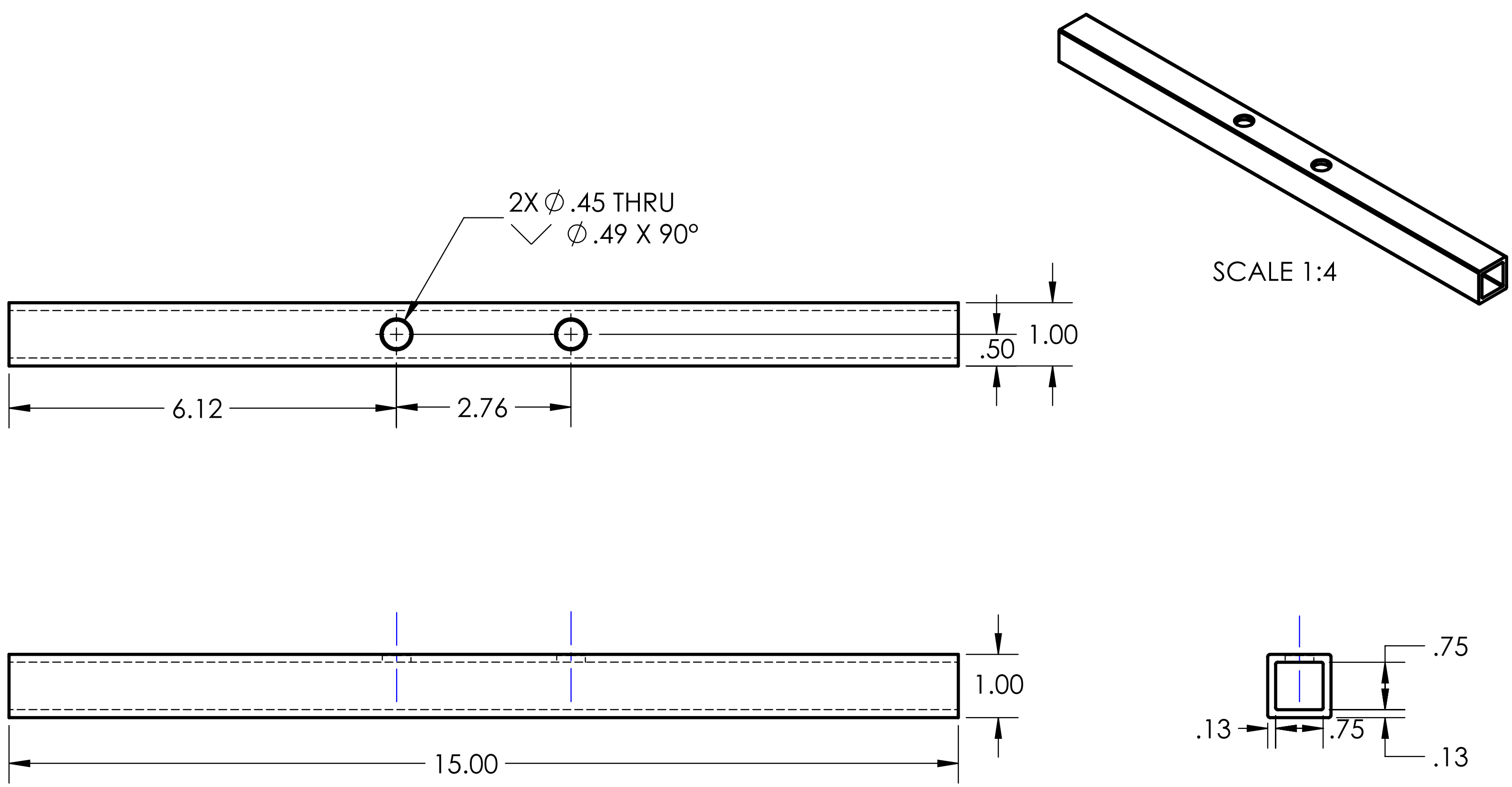
2 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	F51 SUSTAINABLE ENERGY STORAGE
1. ALL DIMS. IN INCHES 2. TOLERANCES: X.XX = ±.01 X.XXX = ±.005 ANGLES = ±1° 3. INSIDE TOOL RADIUS .02 MAX. 4. BREAK SHARP EDGES .01 MAX. 5. 63 √ FAO	DRAWN	AC	3/7	TITLE:
	CHECKED	JL	3/7	SQUARE TUBE STOCK (10.5")
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL 4130 ALLOY STEEL	COMMENTS:			SIZE: A · DWG. NO. 15210 · REV
DO NOT SCALE DRAWING				SCALE: 1:1.5 · SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	F51 SUSTAINABLE ENERGY STORAGE
1. ALL DIMS. IN INCHES 2. TOLERANCES: X.XX = ±.01 X.XXX = ±.005 ANGLES = ±1° 3. INSIDE TOOL RADIUS .02 MAX. 4. BREAK SHARP EDGES .01 MAX. 5. 63 √ FAO	DRAWN	AC	3/7	TITLE: SQUARE TUBE STOCK (10.5" W/ HOLE)
	CHECKED	JL	3/7	
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL 4130 ALLOY STEEL	COMMENTS:			SIZE A · DWG. NO. 15220 · REV
DO NOT SCALE DRAWING				SCALE: 1:2 · SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

1. ALL DIMS. IN INCHES
2. TOLERANCES:
   X.XX = ±.01
   X.XXX = ±.005
   ANGLES = ±1°
3. INSIDE TOOL RADIUS .02 MAX.
4. BREAK SHARP EDGES .01 MAX.
5. 63 FAO

MATERIAL
4130 ALLOY STEEL

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	AC	3/7
CHECKED	JL	3/7
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

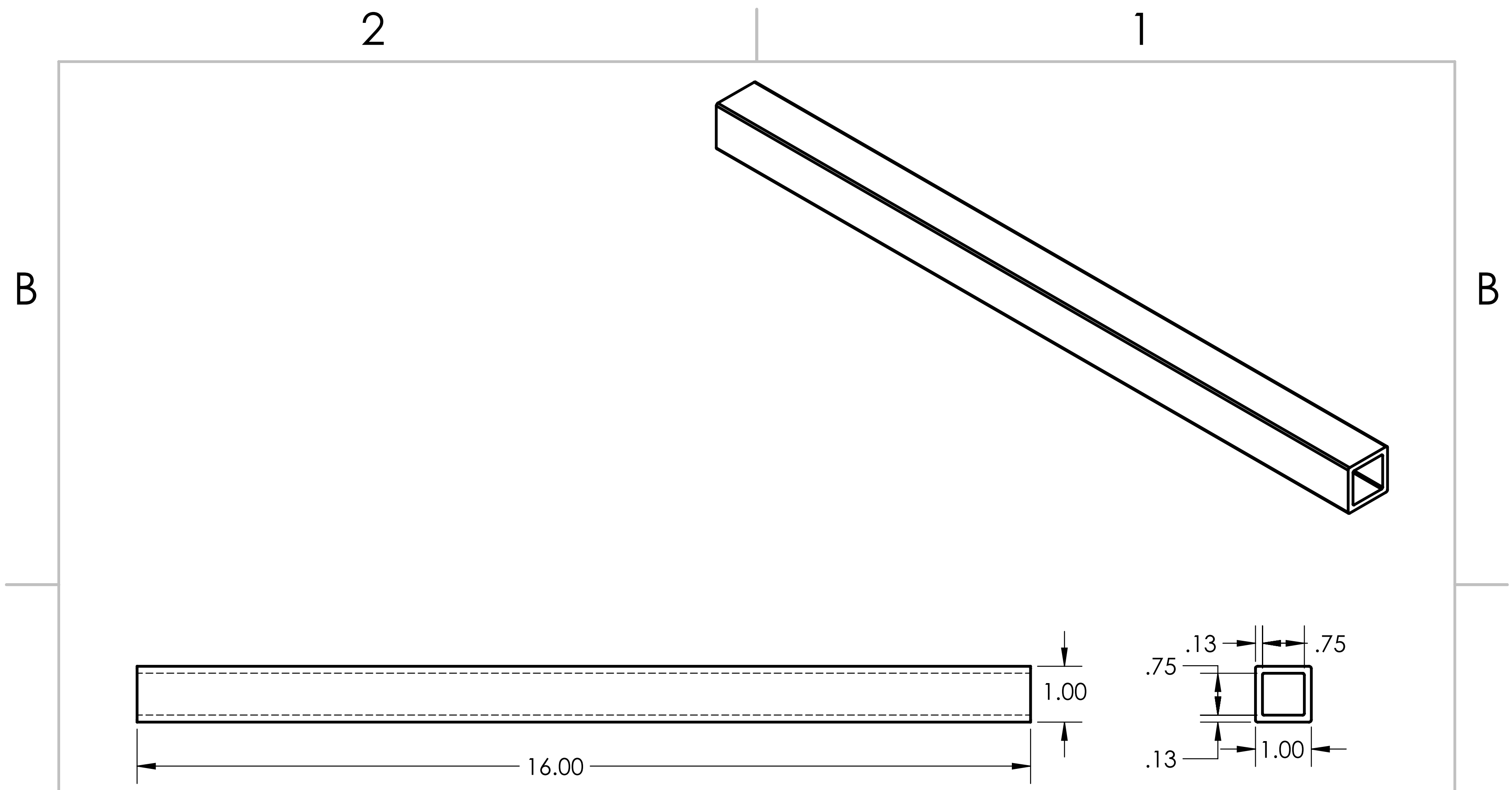
F51 SUSTAINABLE ENERGY STORAGE

TITLE:

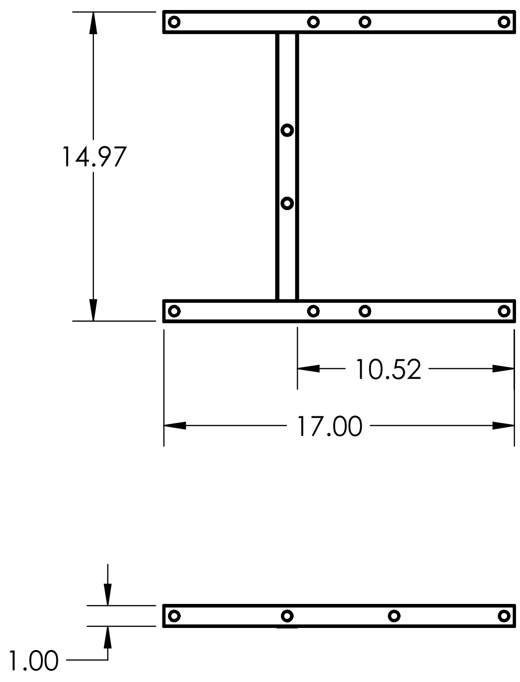
SQUARE TUBE STOCK (15" LOWER)

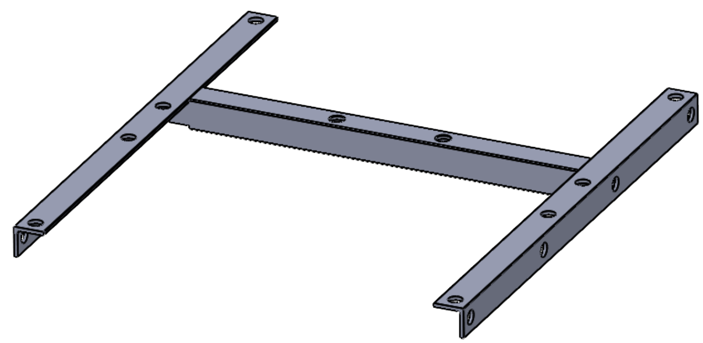
SIZE	DWG. NO.	REV
A	15230	

SCALE: 1:2.5 SHEET 1 OF 1

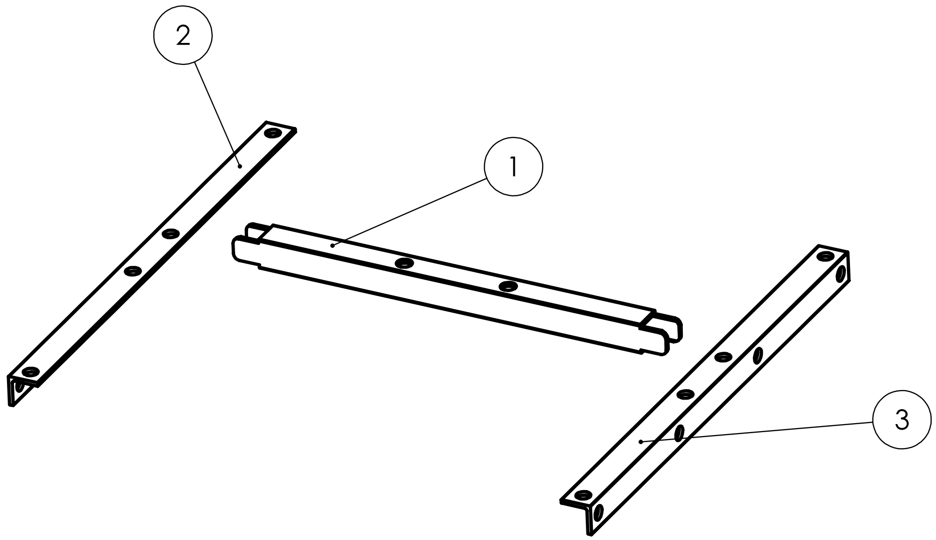


UNLESS OTHERWISE SPECIFIED:		NAME	DATE	F51 SUSTAINABLE ENERGY STORAGE
1. ALL DIMS. IN INCHES 2. TOLERANCES: X.XX = ±.01 X.XXX = ±.005 ANGLES = ±1° 3. INSIDE TOOL RADIUS .02 MAX. 4. BREAK SHARP EDGES .01 MAX. 5. 63 √ FAO	DRAWN	AC	3/7	TITLE:
	CHECKED	JL	3/7	SQUARE TUBE STOCK (16")
	ENG APPR.			
	MFG APPR.			
	Q.A.			
	COMMENTS:			SIZE A — DWG. NO. 15240 — REV
MATERIAL 4130 ALLOY STEEL				
DO NOT SCALE DRAWING				SCALE: 1:2.5 — SHEET 1 OF 1





UNLESS OTHERWISE SPECIFIED:		NAME	DATE	F51 SUSTAINABLE ENERGY STORAGE
1. ALL DIMS. IN INCHES 2. TOLERANCES: X.XX = ±.01 X.XXX = ±.005 ANGLES = ±1° 3. INSIDE TOOL RADIUS .02 MAX. 4. BREAK SHARP EDGES .01 MAX. 5. 63 √ FAO	DRAWN	JG	3/8	TITLE:
	CHECKED	AC	3/8	WELDED H SUB-ASSYM
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL N/A	COMMENTS:			SIZE A · DWG. NO. 15300 · REV
DO NOT SCALE DRAWING				SCALE: 1:10 · SHEET 1 OF 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	15310	15" CALIPER STOCK MEMBER	1
2	15320	BACK ANGLE IRON	1
3	15330	FRONT ANGLE IRON	1

UNLESS OTHERWISE SPECIFIED:

1. ALL DIMS. IN INCHES
2. TOLERANCES:
   X.XX = ±.01
   X.XXX = ±.005
   ANGLES = ±1°
3. INSIDE TOOL RADIUS .02 MAX.
4. BREAK SHARP EDGES .01 MAX.
5. 63 √ FAO

MATERIAL N/A

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JG	3/8
CHECKED	AC	3/8
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

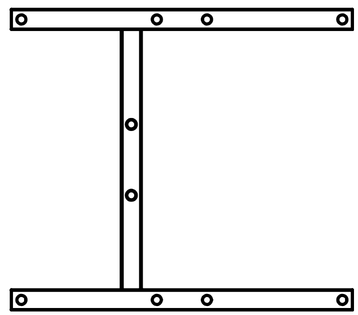
F51 SUSTAINABLE ENERGY STORAGE

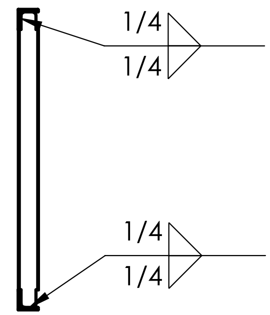
TITLE:

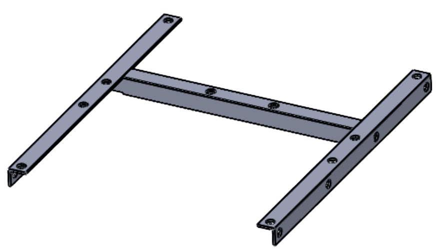
WELDED H SUB-ASSYM

SIZE A | DWG. NO. 15300E | REV

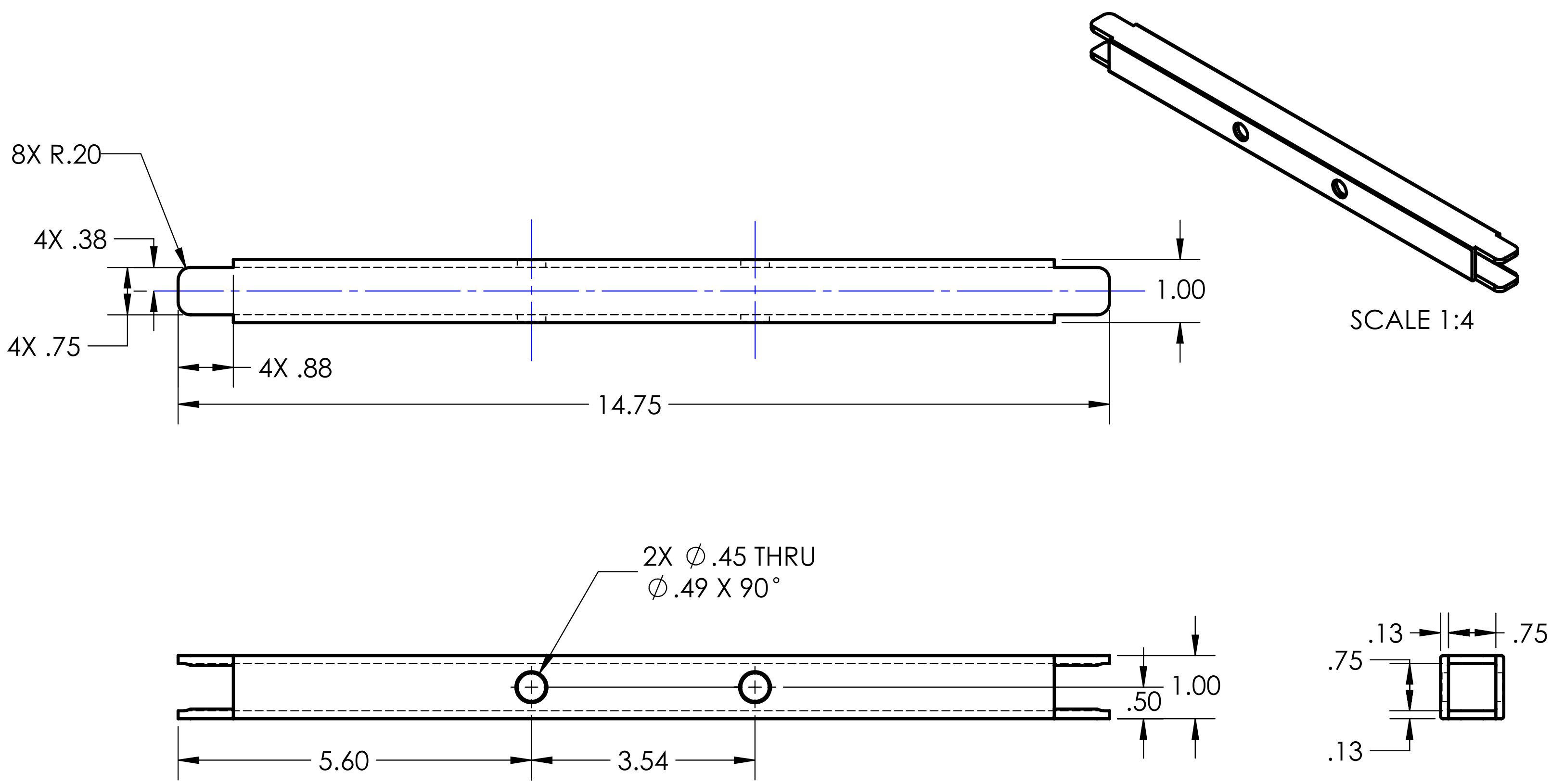
SCALE: 1:10 | SHEET 1 OF 1



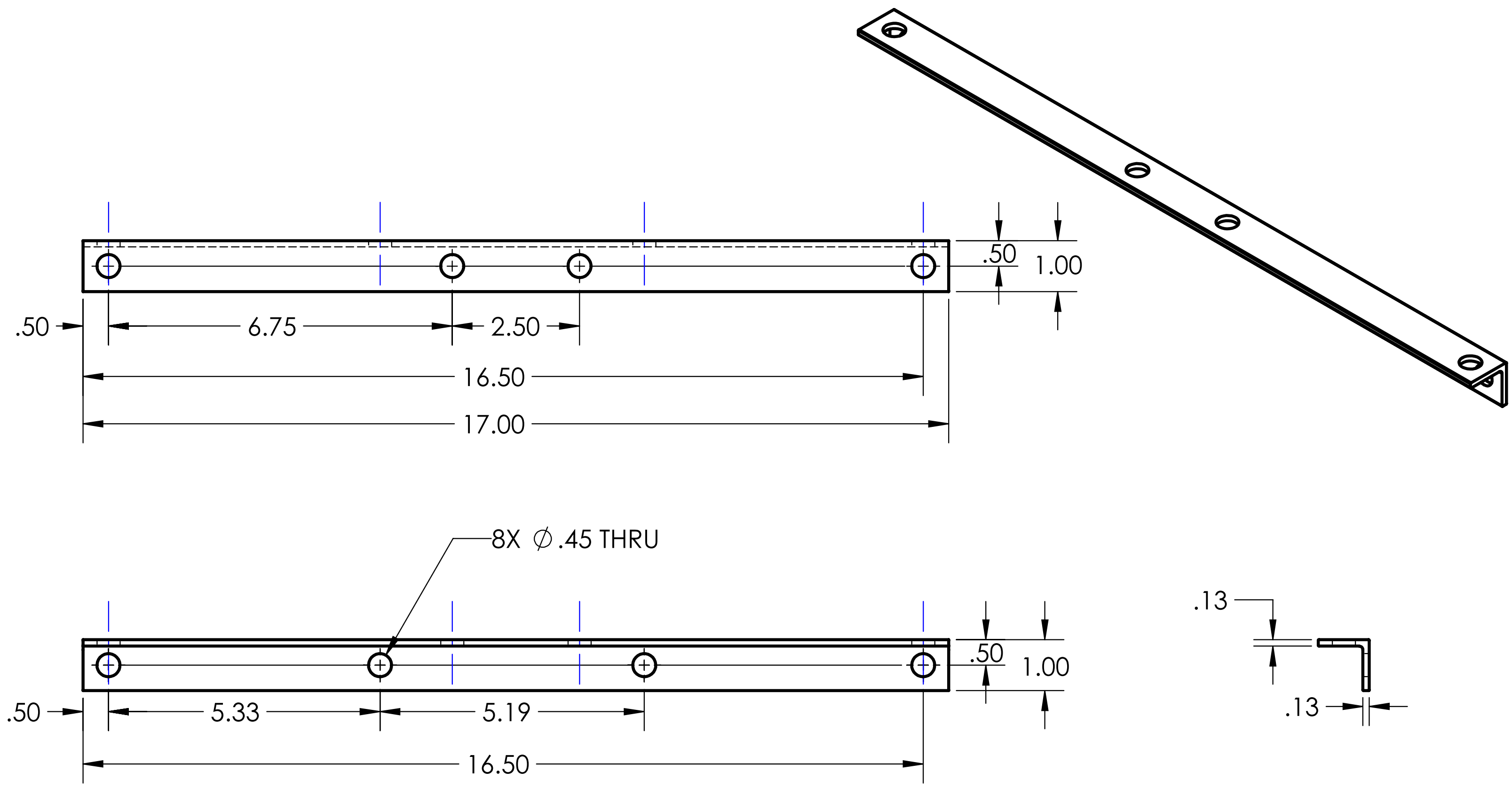




UNLESS OTHERWISE SPECIFIED:		NAME	DATE	F51 SUSTAINABLE ENERGY STORAGE
1. ALL DIMS. IN INCHES 2. TOLERANCES: X.XX = ±.01 X.XXX = ±.005 ANGLES = ±1° 3. INSIDE TOOL RADIUS .02 MAX. 4. BREAK SHARP EDGES .01 MAX. 5. 63 √ FAO	DRAWN	JG	3/8	TITLE:
	CHECKED	AC	3/8	WELDED H SUB-ASSYM
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL N/A	COMMENTS:			SIZE A DWG. NO. 15300W REV
DO NOT SCALE DRAWING				SCALE: 1:10 SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	F51 SUSTAINABLE ENERGY STORAGE
1. ALL DIMS. IN INCHES 2. TOLERANCES: X.XX = ±.01 X.XXX = ±.005 ANGLES = ±1° 3. INSIDE TOOL RADIUS .02 MAX. 4. BREAK SHARP EDGES .01 MAX. 5. 63 FAO	DRAWN	AC	3/7	TITLE:
	CHECKED	JL	3/7	SQUARE TUBE STOCK (15" CALIPER)
	ENG APPR.			
	MFG APPR.			
	Q.A.			
	COMMENTS:			SIZE A DWG. NO. 15310 REV
MATERIAL 4130 ALLOY STEEL				SCALE: 1:2.5 SHEET 1 OF 1
DO NOT SCALE DRAWING				



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
1. ALL DIMS. IN INCHES 2. TOLERANCES: X.XX = ±.01 X.XXX = ±.005 ANGLES = ±1° 3. INSIDE TOOL RADIUS .02 MAX. 4. BREAK SHARP EDGES .01 MAX. 5. 63 √ FAO	DRAWN	AC	3/7
	CHECKED	JL	3/7
	ENG APPR.		
	MFG APPR.		
	Q.A.		
MATERIAL LOW CARBON STEEL	COMMENTS:		
DO NOT SCALE DRAWING			

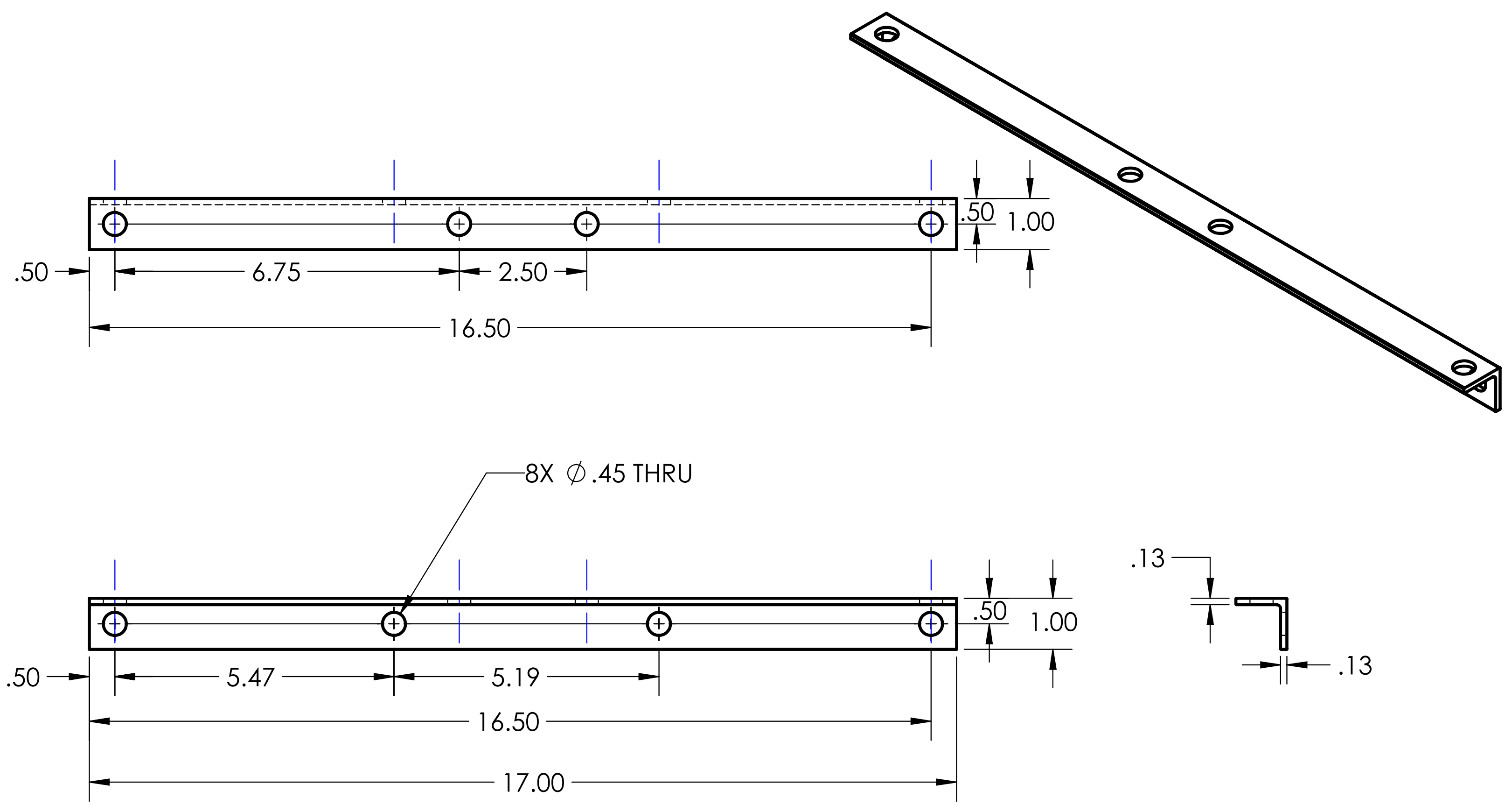
F51 SUSTAINABLE ENERGY STORAGE

TITLE:

BACK ANGLE IRON

SIZE A | DWG. NO. 15320 | REV

SCALE: 1:3 | SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

1. ALL DIMS. IN INCHES
2. TOLERANCES:
   X.XX = ±.01
   X.XXX = ±.005
   ANGLES = ±1°
3. INSIDE TOOL RADIUS .02 MAX.
4. BREAK SHARP EDGES .01 MAX.
5. 63 √ FAO

MATERIAL
LOW CARBON STEEL

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	AC	3/7
CHECKED	JL	3/7
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

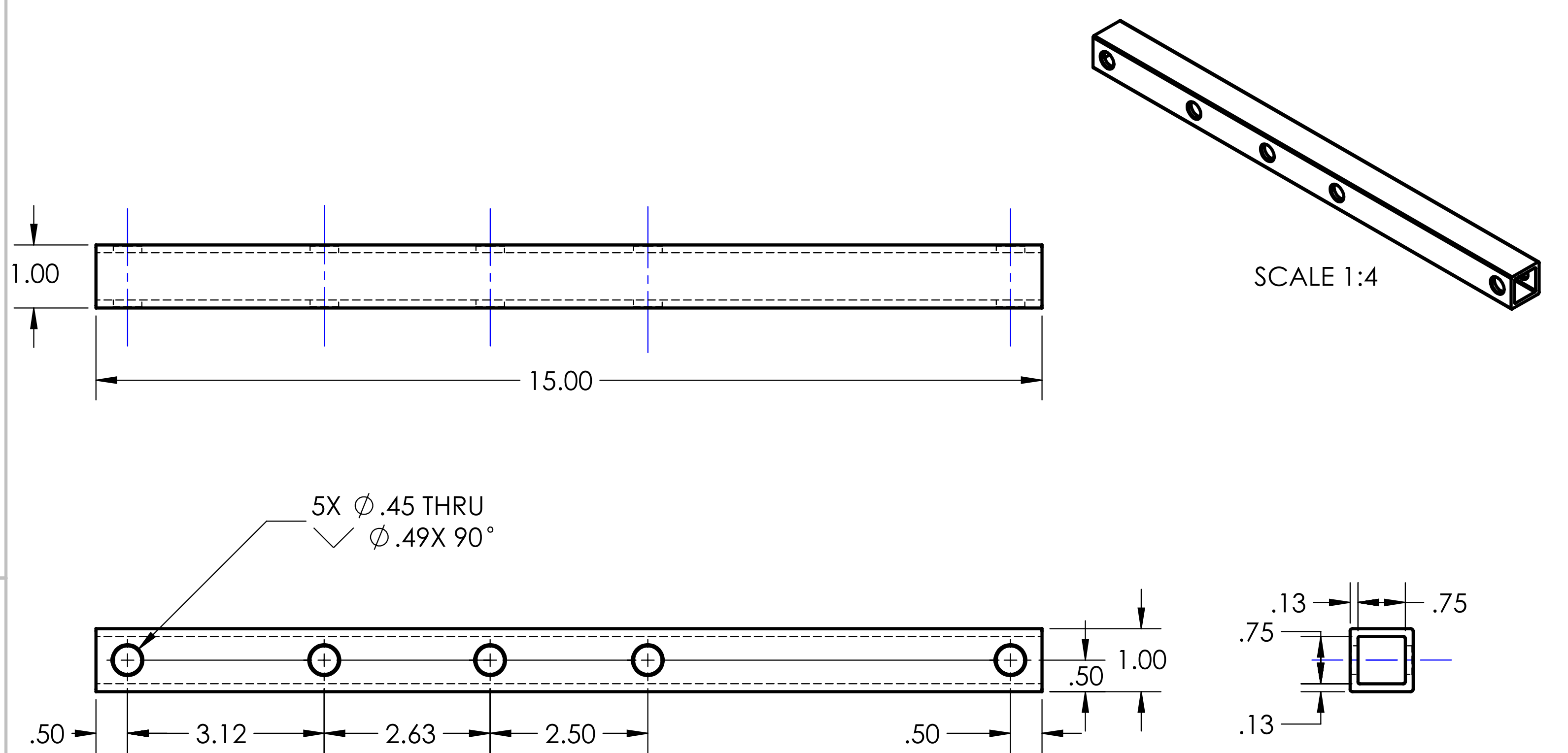
F51 SUSTAINABLE ENERGY STORAGE

TITLE:

FRONT ANGLE IRON

SIZE	DWG. NO.	REV
A	15330	

SCALE: 1:3 SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

1. ALL DIMS. IN INCHES
2. TOLERANCES:
   X.XX = ±.01
   X.XXX = ±.005
   ANGLES = ±1°
3. INSIDE TOOL RADIUS .02 MAX.
4. BREAK SHARP EDGES .01 MAX.
5. 63 FAO

MATERIAL
4130 ALLOY STEEL

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	AC	3/7
CHECKED	JL	3/7
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

F51 SUSTAINABLE ENERGY STORAGE

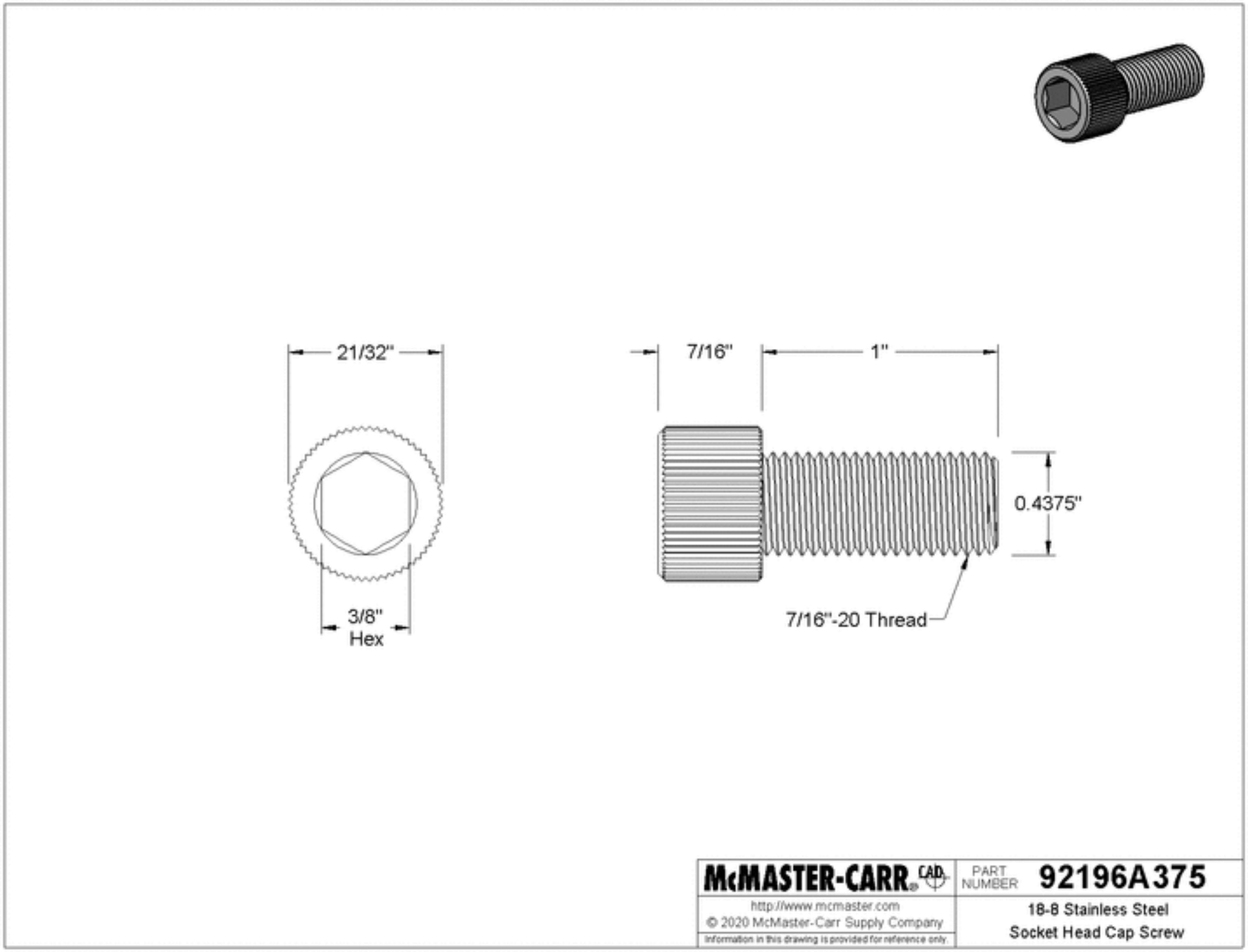
TITLE:

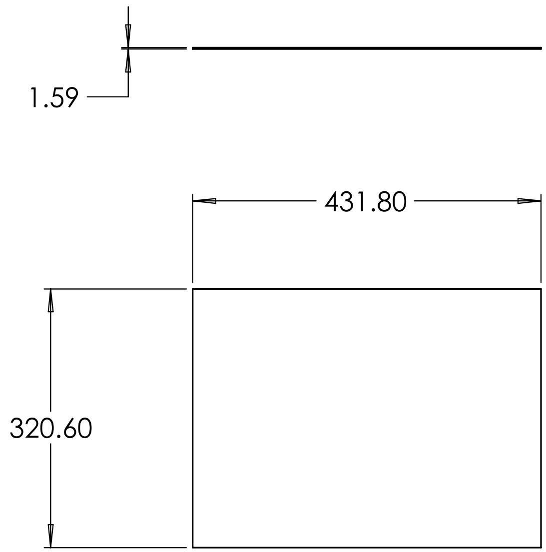
SQUARE TUBE STOCK (15" UPPER)

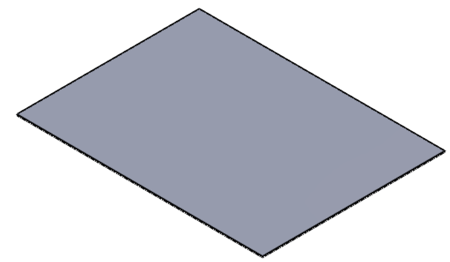
SIZE A | DWG. NO. 15400 | REV

SCALE: 1:2.5 | SHEET 1 OF 1

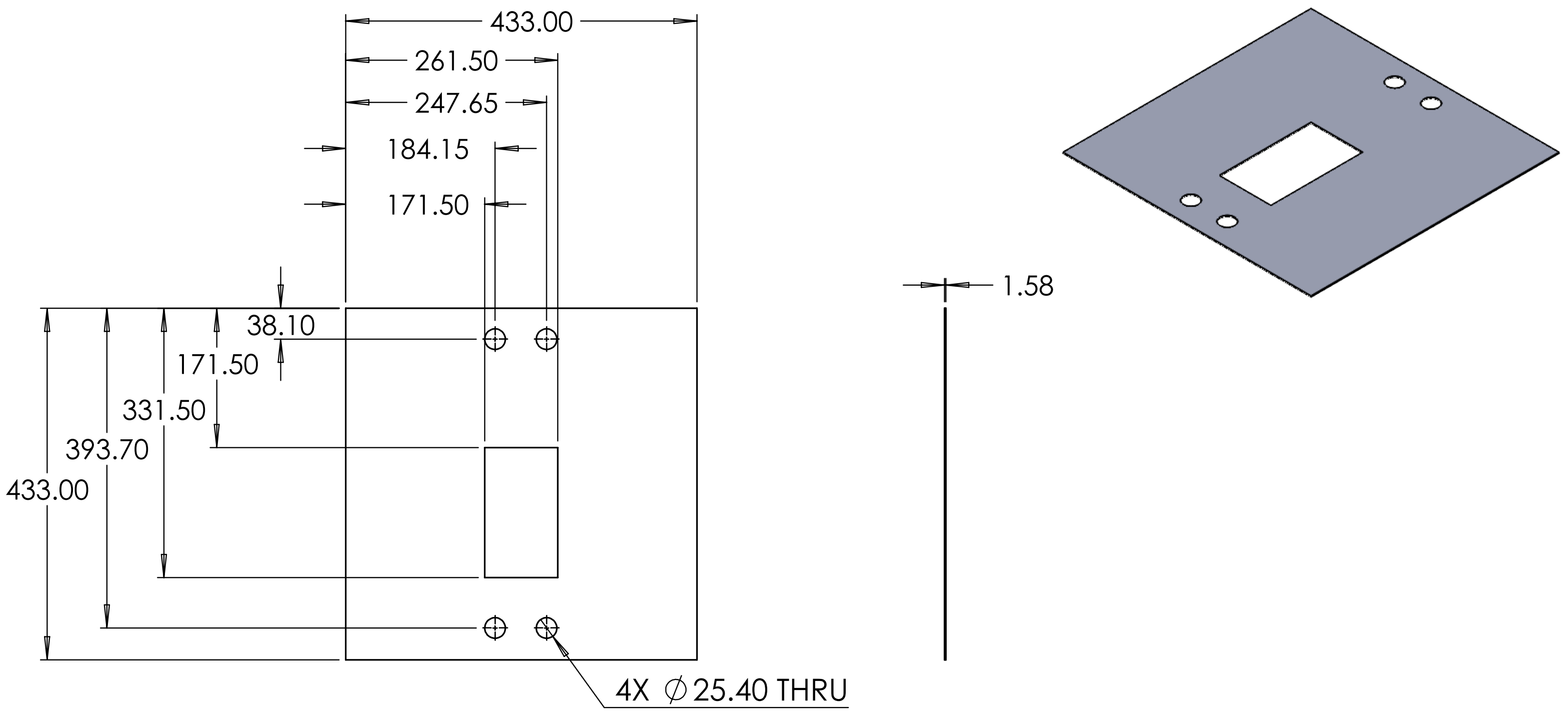
PART NUMBER: 15500



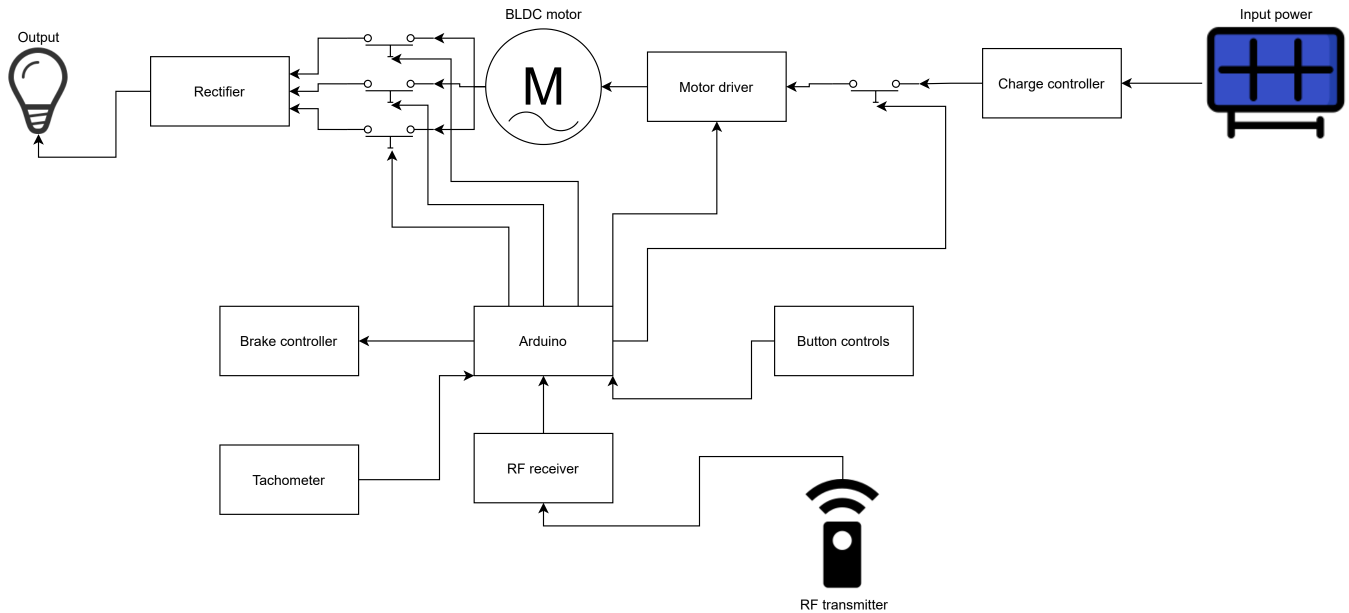




UNLESS OTHERWISE SPECIFIED:		NAME	DATE	F51 SUSTAINABLE ENERGY STORAGE
1. ALL DIMS. IN MILLIMETERS 2. TOLERANCES: X.XX = ±0.10 ANGLES = ±1° 3. INSIDE TOOL RADIUS 0.5 MAX. 4. BREAK SHARP EDGES 0.5 MAX. 5. 1.6 √ FAO	DRAWN	JRL	3/7/2021	TITLE:
	CHECKED	JSG	3/7/2021	SIDE STEEL PLATE
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL LOW-CARBON STEEL	COMMENTS:			SIZE A · DWG. NO. 15700A · REV A
DO NOT SCALE DRAWING				SCALE: 1:8 · SHEET 1 OF 1

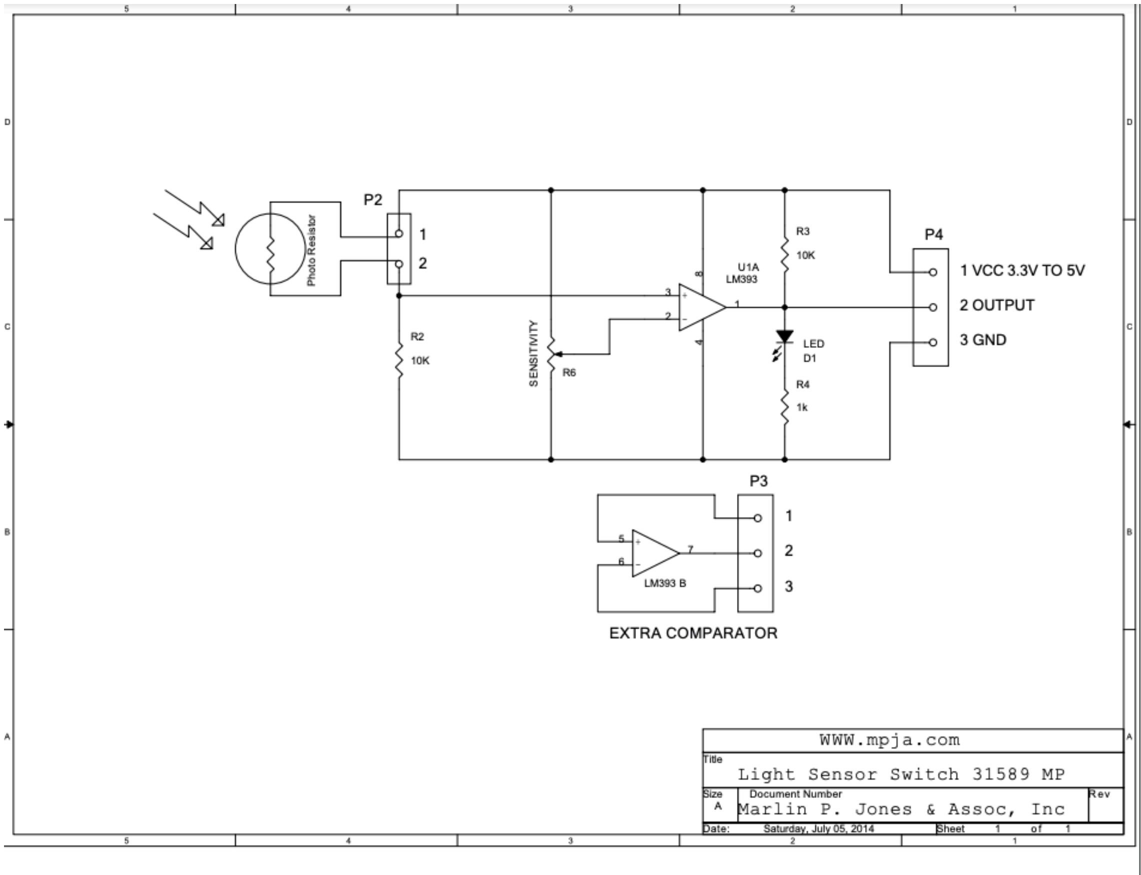


UNLESS OTHERWISE SPECIFIED:		NAME	DATE	F51 SUSTAINABLE ENERGY STORAGE
1. ALL DIMS. IN MILLIMETERS 2. TOLERANCES: X.XX = ±0.10 ANGLES = ±1° 3. INSIDE TOOL RADIUS 0.5 MAX. 4. BREAK SHARP EDGES 0.5 MAX. 5. 1.6 √ FAO	DRAWN	JRL	3/7/2021	TITLE:
	CHECKED	JSG	3/7/2021	TOP STEEL PLATE
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL LOW-CARBON STEEL	COMMENTS:			SIZE A · DWG. NO. 15700B · REV A
DO NOT SCALE DRAWING				SCALE: 1:8 · SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	F51 SUSTAINABLE ENERGY STORAGE
1. ALL DIMS. IN MILLIMETERS 2. TOLERANCES: X.XX = ±0.10 ANGLES = ±1° 3. INSIDE TOOL RADIUS 0.5 MAX. 4. BREAK SHARP EDGES 0.5 MAX. 5. 1.6 √ FAO	DRAWN	NS	3/7/21	TITLE:
	CHECKED	JL	3/7/21	CONTROL SYSTEM ASYM
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL N/A	COMMENTS:			SIZE A / DWG. NO. 16000 / REV A
DO NOT SCALE DRAWING				SCALE: 1:10 / SHEET 1 OF 1

PART NUMBER: 16100



Description:

Module is used to detect ambient light. The sensor is a CDS photo resistor connected to a LM393 voltage comparator IC with adjustable sensitivity control (R6). The LED indicator that turns on when dark or low light is detected. The output can be connected directly to a micro-controller I/O port or a relay. Ideal for turning on lights automatically at night.

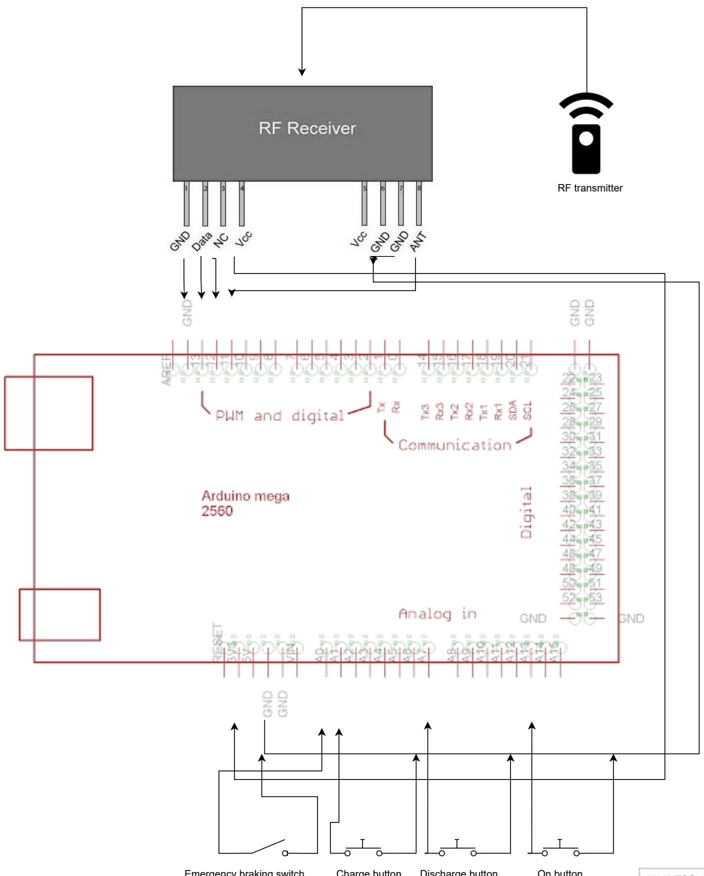
Power: 3.3V to 5VDC

Supply Current: < 1mA (LED off)

Output: Digital TTL Open Collector Current sink 20mA

3 Pin .1in. Pitch Header for Power & Output

L: 1-1/4” W: 5/8” T: 1/2” WT: .02



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
1. ALL DIMS. IN MILLIMETERS 2. TOLERANCES: X.XX = ±0.10 ANGLES = ±1° 3. INSIDE TOOL RADIUS 0.5 MAX. 4. BREAK SHARP EDGES 0.5 MAX. 5. 1.6 FAO	DRAWN	NS	3/7/21
	CHECKED	JL	3/7/21
	ENG APPR.		
	MFG APPR.		
	Q.A.		
MATERIAL N/A	COMMENTS:		
DO NOT SCALE DRAWING			

F51 SUSTAINABLE ENERGY STORAGE

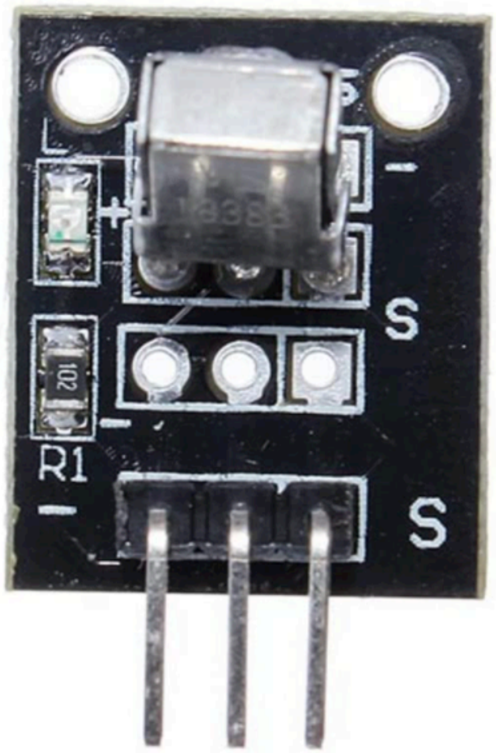
TITLE:

INPUT SYSTEM ASSEMBLY

SIZE	DWG. NO.	REV
A	16200	A

SCALE: 1:10 SHEET 1 OF 1

PART NUMBER: 16210

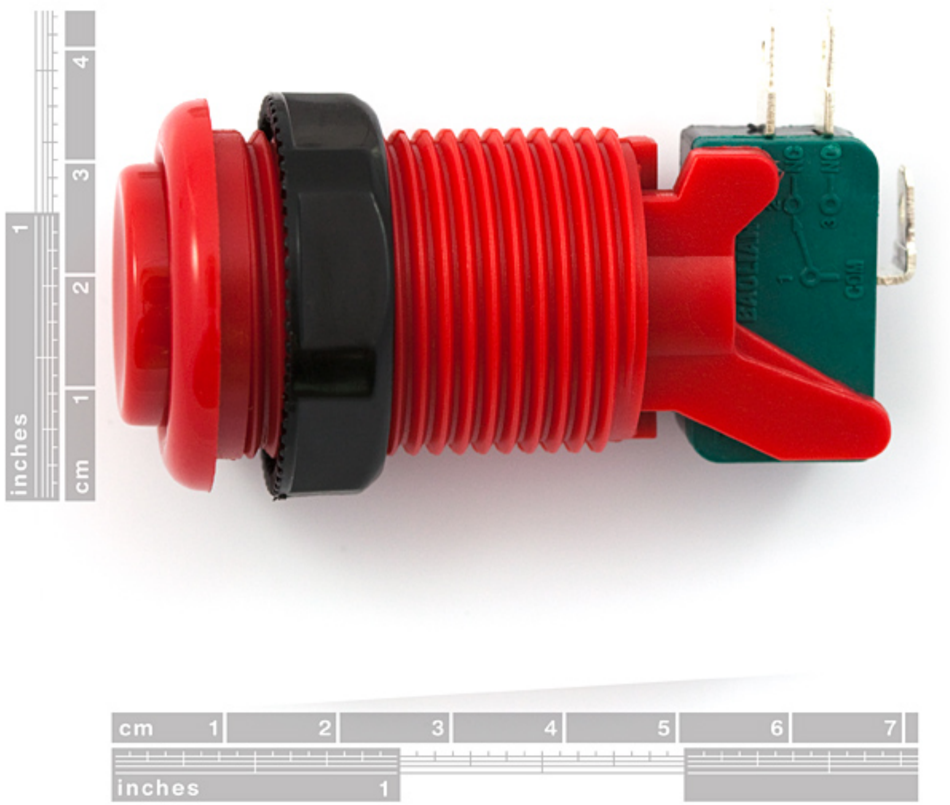


Description: IR receiver module can receive standard 38KHz modulation remote control signal. You can decode the remote-control signal through Arduino programming.

PART NUMBER: 16220

Description: This mini slim infrared remote control with 20 function keys. It can transmit distances up to 8 meters. Ideal for handling a variety of equipment indoors.

PART NUMBER: 16230



Description:

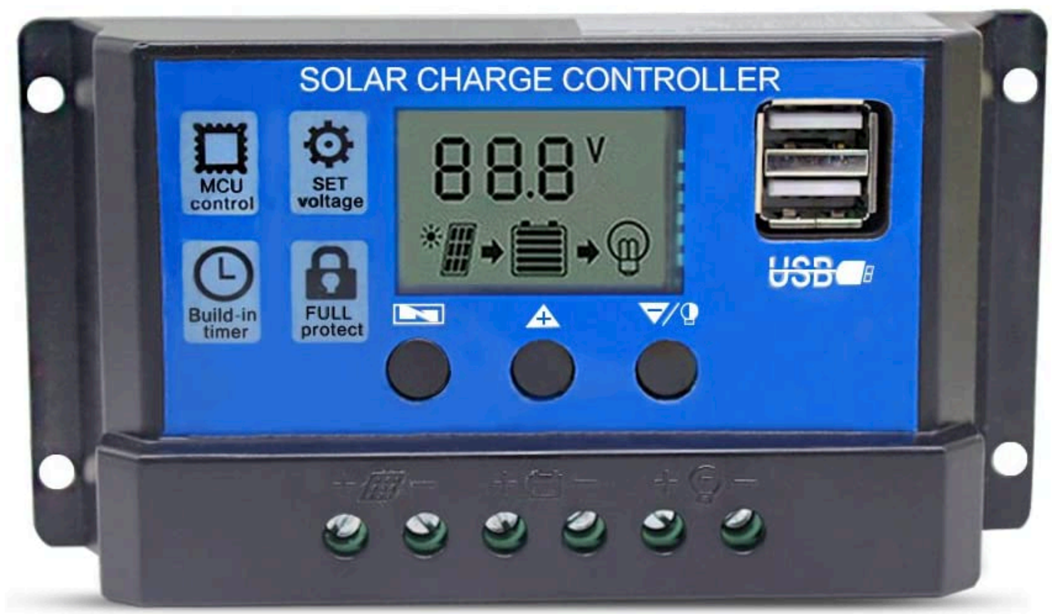
- Concave plunger design
- Durable nylon material
- Microswitch: max 3A @ 120 VAC
- Microswitch reliability tested to 10,000,000 cycles
- Includes 3 terminal microswitch
- Net weight: 25g* Bezel diameter: 32mm
- Overall height: 65mm
- Mounting hole: 1 1/8th inch paddle bit (1.125" / 28mm)

PART NUMBER: 16240

Description:

- Rated for 12V 20A
- Includes Missile Switch Cover
- Illuminated
- Note: The LED can be illuminated with as low as 3.3V.

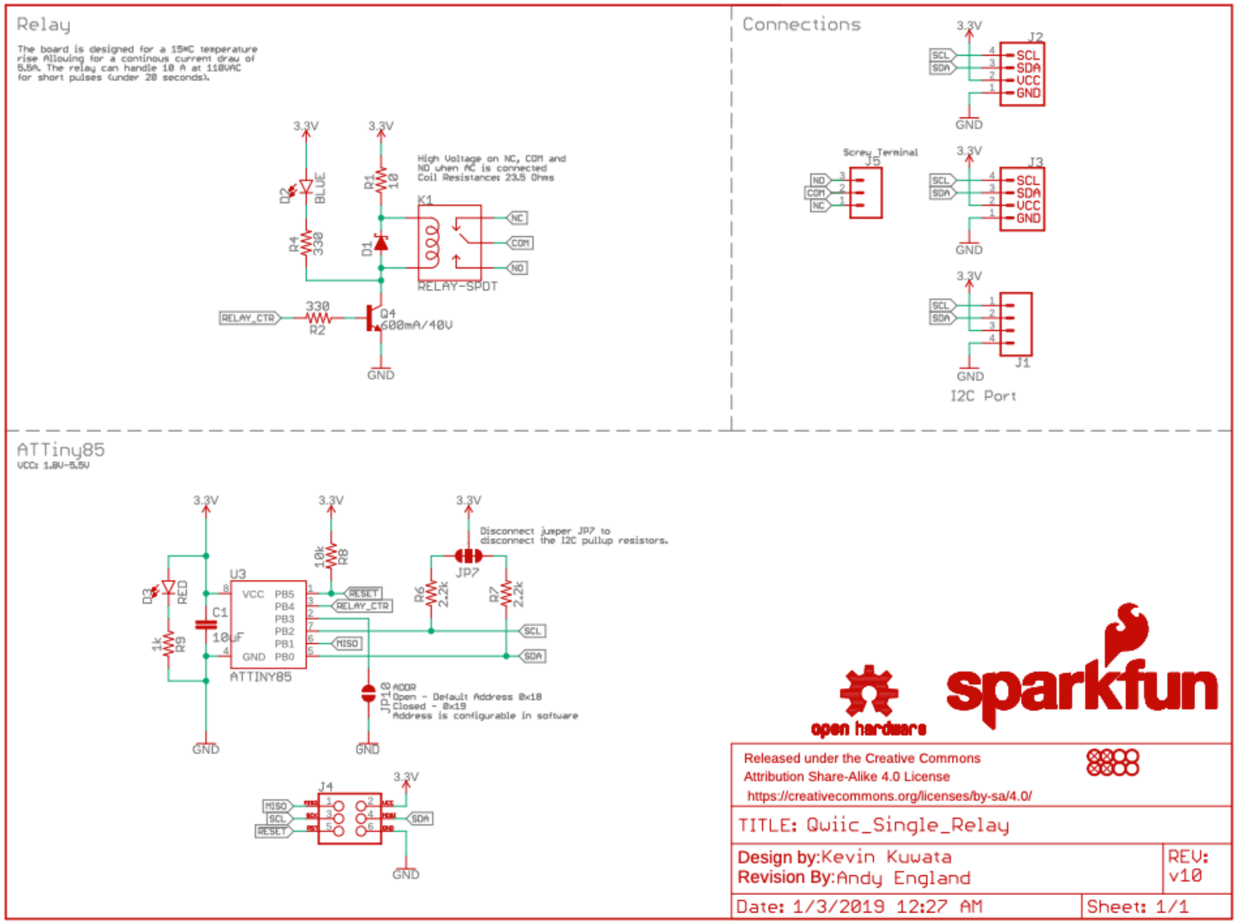
PART NUMBER: 16300



Description:

- 20A Solar Charge controller : Binen solar charger controller are UL 1741 certified, the solar charger controller compatibility with 12V 24V system. Discharge Current: 10A,build-in industrial micro controller, automatically manage the working of solar panel and battery in solar system. Dual USB output 5V/2.5A (max), to support mobile phone charging.
- Multiple Protection Functions: Binen solar controller has short-circuit protection, open-circuit protection, reverse protection, over-load protection. Fully 3-stage PWM charge management, improve system efficiency and prolong the life span of the battery.
- Battery Type: The charge regulator is only suitable for lead-acid batteries: OPEN, AGM, GEL, it is not suited for nickel hydride, lithium, Liions, or other batteries. For protecting the lifespan of your battery, once the voltage of the battery drops below 8V, the solar controller will turn off automatically.
- LCD Display: Comes with a display that can clearly indicate the status and data, it can be conveniently switched modes and parameter configuration, suitable for home, industrial, commercial etc.
- Easy to Install and Operate: The charge controller should connect the battery first, then the solar panel, and finally the load! The disassembly sequence is contrary to the wiring order. Dual mosfet Reverse current protection, low heat production. (Note: The charge controller will heat up when it is running. Please be careful to install the charger controller on a flat, well-ventilated place)

PART NUMBER: 16400



Description:

- Operating Voltage: 1.7V-3.6V
- Coil Resistance: 23.5Ω
- I^2C Address: 0x18 (Default), (Jumper changes to 0x19)
- Max Current (Through Relay): 5.5A (240 VAC)

PART NUMBER: 16500

Description:

- Packing with international standard.
- The welding structure Super temperature properties and power-cycle capacity.
- Forward-direction voltage is decreasing.
- Convert your three-phase current input into DC with this bridge Rectifier.
- This bridge Rectifier can be used in a wide variety of applications.

PART NUMBER: 16600

Description:

- Package includes: 20cm (7.9inch) / 40pin Female to Female jumper wires / 40pin Male to Female jumper wires / 40pin Male to Male jumper wires (Total 120pcs)
- Connector Type: Standard 2.54mm pitch dupont housing connector / 1pin-1pin
- Cable length: 20cm (7.9 inch) / Cable material: 12-core pure copper wire
- Cable features: Separable multicolored (10 colors) softness ribbon cables
- For DIY experiment / Electronic projects / Breadboard / PC motherboard / PCB project

PART NUMBER: 16700

Description:

- 100-feet of primary wire
- 18-gauge red
- PVC outer-jacket resists water, oil, chemicals and abrasion

Appendix O. Control System Code

```
#include "Arduino.h"
#include <stdio.h>
#include <stdarg.h>
#define INCSPEED 5

const int chargeButtonPin = A11;
const int dischargeButtonPin = A8;
const int stopButtonPin = A10;
const int onButtonPin = A9;
const int brakeButtonPin = A12;

const int greenledPin = 22;

const int relay1Pin = 24;
const int relay2Pin = 25;
const int relay3Pin = 26;
const int relay4OutPin = 27;

const int speedOutPin = 2;
const int motorOnPin = 34;
const int runBrakePin = 33;
const int M0 = 31;
const int M1 = 28;
const int VM = 11;
const int VL = 10;
const int TL = 50;

float pulses = 0;
unsigned long oldTime = 0;
unsigned long oldIncTime = 0;
unsigned long inc_time = 0;
int inc_speed = 8;
unsigned long new_time;
enum{OFF, CHARGE, DISCHARGE, BRAKE};

void setup() {
  Serial.begin(9600);
  delay(500);
  pinMode(speedOutPin, INPUT_PULLUP);
  pinMode(motorOnPin, OUTPUT);
  pinMode(runBrakePin, OUTPUT);
  pinMode(M0, OUTPUT);
  pinMode(M1, OUTPUT);
  pinMode(VM, OUTPUT);
  pinMode(VL, OUTPUT);
  pinMode(TL, OUTPUT);
  pinMode(relay1Pin, OUTPUT);
  pinMode(relay2Pin, OUTPUT);
  pinMode(relay3Pin, OUTPUT);
```

```
  pinMode(relay4OutPin, OUTPUT);
  digitalWrite(M0, LOW);
  digitalWrite(M1, LOW);
  digitalWrite(TL, HIGH);
  digitalWrite(relay1Pin, LOW);
  digitalWrite(relay2Pin, LOW);
  digitalWrite(relay3Pin, LOW);
  digitalWrite(relay4OutPin, LOW);
  oldTime = millis();
  attachInterrupt(0,speed_isr,FALLING);  //attaching the interrupt
  analogWrite(VM, inc_speed);
  analogWrite(VL, 0);
}

void loop() {
  static int state = OFF;
  state = getState();
  switch (state) {
    case OFF:
      offState();
    break;

    case CHARGE:
      chargeState();
    break;

    case DISCHARGE:
      dischargeState();
    break;

    case BRAKE:
      brakeState();
    break;
  }
}

int getState() {
  static int state = OFF;
  int on = analogRead(onButtonPin) > 500;
  int brake = analogRead(brakeButtonPin) > 500;
  int charge = analogRead(chargeButtonPin) > 500;
  int discharge = analogRead(dischargeButtonPin) > 500;
  int stopped = analogRead(stopButtonPin) > 500;

  if (!on) {
    state = OFF;
    return state;
  }
  if (brake) {
    state = BRAKE;
    return state;
```

```
  }
  if (charge) {
    state = CHARGE;
    return state;
  }
  if (discharge) {
    state = DISCHARGE;
    return state;
  }
  if (stopped) {
    state = OFF;
    return state;
  }
  return state;
}

void offState() {
  //Serial.println("OFF");
  motorOff();
  outputOff();
  inputOn();
}

void chargeState() {
  //Serial.println("CHARGE");
  inputOn();
  outputOff();
  motorOn();
}

void dischargeState() {
  //Serial.println("DISCHARGE");
  outputOn();
  delay(200);
  inputOff();
  delay(200);
  motorOff();
}

void brakeState() {
  //Serial.println("BRAKE");
  inputOn();
  outputOff();
  motorBrake();
}

void inputOff() {
  digitalWrite(relay1Pin, HIGH);
  digitalWrite(relay2Pin, HIGH);
  digitalWrite(relay3Pin, HIGH);
}
```

```
void inputOn() {
  digitalWrite(relay1Pin, LOW);
  digitalWrite(relay2Pin, LOW);
  digitalWrite(relay3Pin, LOW);
}

void outputOn() {
  digitalWrite(relay4OutPin, HIGH);
}

void outputOff() {
  digitalWrite(relay4OutPin, LOW);
}

void speed_isr() {
  pulses++;
  new_time = millis() - oldTime;
  inc_time = millis() - oldIncTime;
  if (new_time >= 1000) {
    int rpm = (pulses / new_time) * 200;
    oldTime = millis();
    pulses = 0;
    Serial.println(rpm);
    Serial.println(millis());
  }
  if (inc_time >= 5000) {
    if (inc_speed <= 205) {
      if (inc_speed > 150) {
        inc_speed += INCSPEED;
        oldIncTime = millis();
        analogWrite(VM, inc_speed);
      }
      else {
        inc_speed += INCSPEED;
        oldIncTime = millis();
        analogWrite(VM, inc_speed);
      }
    }
  }
}

void motorOn() {
  digitalWrite(motorOnPin, LOW);
  digitalWrite(runBrakePin, LOW);
}

void motorOff() {
  digitalWrite(motorOnPin, HIGH);
  digitalWrite(runBrakePin, LOW);
}
```

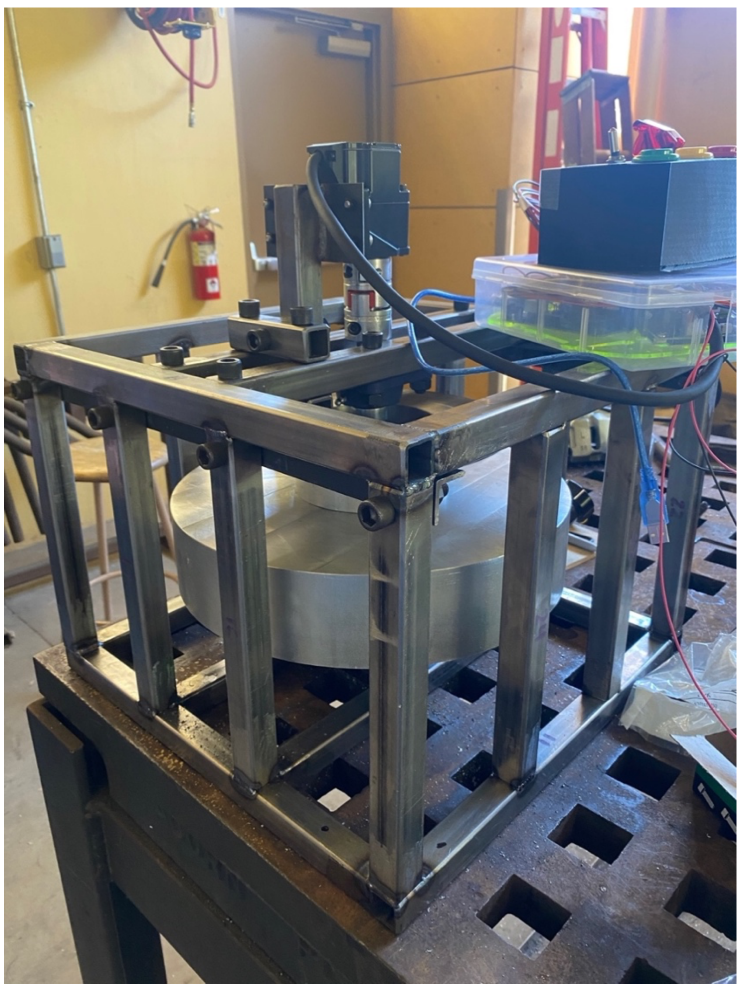
```
void motorBrake() {
  digitalWrite(runBrakePin, HIGH);
  digitalWrite(motorOnPin, HIGH);
}
```

Appendix P. User Manual

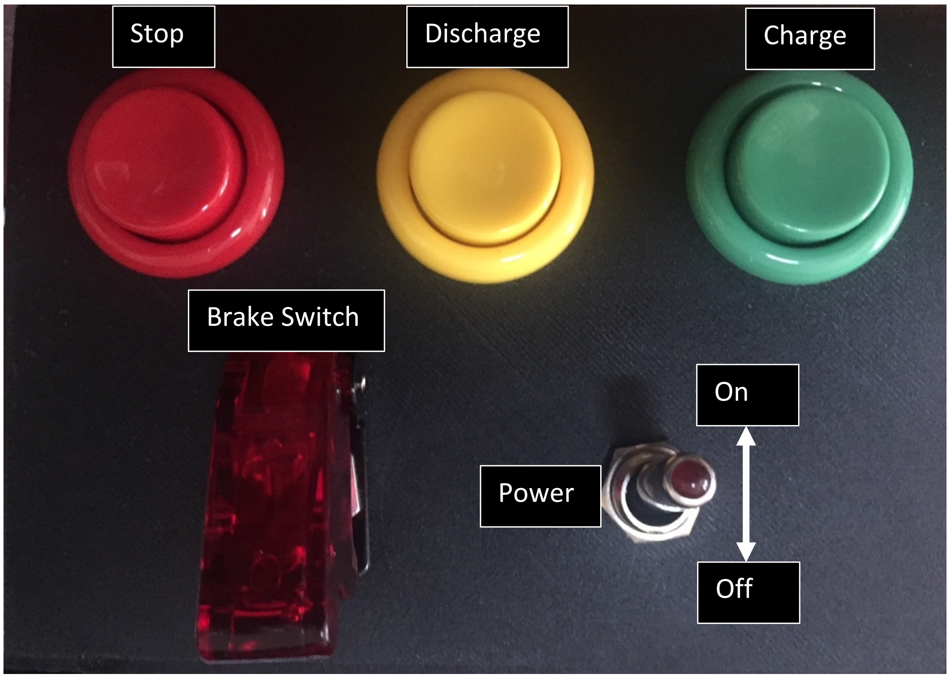
Flywheel Energy Storage System
User Manual

Written by Team F51: Alyse Coonce, Jack Linchey, Nick Schnorr, Jake Grillo

Spring 2021



Setup and Safety Instructions



System Control Box

1. Before plugging in system, ensure that there are no loose or unplugged wires that can get tangled in the system while running.

2. Be sure to wear the proper PPE before starting, including safety glasses. Do not stand near the system while it is running.

3. Ensure that the power switch on the control box is in the off position. Switch will light up.

4. Test that the manual emergency brake will engage when pumped.

5. Connect the desired load to the output terminal.

6. Connect the 24 V power supply to the motor and connect the Arduino USB to either a power cube or computer.

7. Turn on power switch.

8. Press charge button (green) and flywheel will begin to rotate

9. Once fully charged, press discharge (yellow). Power will be supplied to the connected load and the flywheel will begin to decelerate.

10. To stop the power output, press the stop button (red).

11. To engage the motor brake, flip up the brake switch cover and turn the switch to the on position. The flywheel will brake quickly.

12. To engage the manual brake, first make sure that the system is not in charge mode. Pull the lever forcefully.

Maintenance and Part Replacement

- Until frame and all steel parts are painted, the energy storage system should be left inside to avoid weathering/rust
- A parts list can be found in Appendix XX
- Drawings and images of specific parts can be found in Appendix XX
- All electronics parts can be easily accessed and replaced by opening the components box
- Any machined parts can be accessed by the following steps:
    - Loosen the set screw on the motor shaft coupler and remove it off the shaft
    - Unbolt the steel plate on the top of the system
    - Unbolt the two middle bar stock and remove

Parts List:

Assembly Level	Part Number	Description Lvl0	Lvl1	Lvl2	Lvl3	Lvl4	Qty	Source	More Info
0	10000	Final Assembly							
1	11000		Flywheel Assy						
2	11100			Flywheel			1	McCarthy Steel	Customized piece
2	11200			Shaft			1	Misumi	Customized piece directly fro
2	11300			Retaining ring			1	McMaster	Item 97633A300 (Pack of 50)
2	11400			Flywheel Bolts - 60mm			4	McMaster	Item 92095A442
2	11500			Machine Key			1	McMaster	Item 98870A143 (Pack of 5)
1	12000		Braking Assy						
2	12100			Brake Rotor & Pads			1	Summit Racing	PWR-KOE772
2	12200			Hydraulic Handbrake			1	Amazon	B005-BLACK
2	12300			Brake Line Fittings			1	Summit Racing	EAR-581533ERL
2	12400			Brake Line			1	Summit Racing	ZEX-NS6670CB
2	12500			Caliper			1	Summit Racing	Item L1378A
2	12600			Brake Spacer			1	McMaster	Item 1610T49
1	13000		Bearing Assy						
2	13100			25mm Radial Bearings			1	McMaster	Item 5967K84
2	13200			20mm Radial Bearings			1	McMaster	Item 5967K82
2	13300			Housing Bolts			1	McMaster	Item 91251A004 (10 Pack)
2	13400			Housing Nuts			1	McMaster	Item 95479A215 (25 Pack)
2	13500			Thrust Bearing Housing			1	McMaster	Item 1388K504
2	13600			Thrust Bearing			1	Motion Industries	Item NTA-1018
1	14000		Motor Assy						
2	14100			Motor and Controller			1	OrientalMotor	Item BLHM230KC-5 / BLH2D3

2	14200		Shaft Coupler		1	OrientalMotor	Item MCS401020
2	14300		Motor Mounting Bracket		1	OrientalMotor	Item SOL2A-A
2	14400		M5 16mm Bolts		1	McMaster	Item 91292A126 (100 Pack)
2	14500		2.5" Large Bolts		1	McMaster	Item 91251A005 (5 Pack)
2	14600		M5 Nuts		1	McMaster	Item 90592A095 (100 Pack)
2	14700		Square Tube Stock (3.5")		2	McCarthy Steel	
2	14800		Square Tube Stock (6.6")		1	McCarthy Steel	
2	14900		Mounting Plate		1	McCarthy Steel	Recycle from Top steel Plate C
1	15000	Chassis Assy					
2	15100		7/16"-20 Nut		0	Mcmaster	Item 95479A215 - Extra from I
2	15200A		Square Tube Stock (10.5")		4	McCarthy Steel	10.5" Length w/ no holes
2	15200B		Square Tube Stock (10.5" w/ holes)		8	McCarthy Steel	10.5" Length w/ top hole for A
2	15300A		Square Tube Stock (15" Upper)		2	McCarthy Steel	
2	15300B		Square Tube Stock (15" Lower)		2	McCarthy Steel	
2	15300C		Square Tube Stock (15" Caliper)		1	McCarthy Steel	
2	15400		Square Tube Stock (16")		8	McCarthy Steel	
2	15500		7/16" x 20, Screw 1"		2	McMaster	Item 90128A402 (10 Pack)
2	15600A		Back Angle Iron 1" x 1" (17")		1	McMaster	Backside with 4 holes - 9017K
2	15600B		Front Angle Iron 1" x 1" (17")		1	McMaster	Frontside with 4 holes - 9017K
2	15700A		Side Steel Plate		4	McCarthy Steel	
2	15700B		Top Steel Plate		1	McCarthy Steel	
1	16000	Control System Assy					
2	16100		Tachometer		1	MPJA	Item 35029 MP
2	16200		Input System Assy				
3	16210			Receiver	1	Amazon	Item B01EE4VXS0
3	16220			Transmitter	1	Amazon	Item B01EE4VXS0
3	16230			Buttons	3	Sparkfun	Item COM-09336

3	16240		Switches	2	Sparkfun	Item COM-11310
2	16300	Charge controller		1	Amazon	Item B072MMDY4F
2	16400	Relay		4	Sparkfun	Item COM-15093
2	16500	Rectifier		1	Amazon	Item B01JKRIPUK
2	16600	Jumper Wire Kit		1	Amazon	Item PRT-11709
2	16700	Wire spool		1	Amazon	Item 55667423
	Totals		Parts	79		

Appendix Q. Test Procedures

Test Procedure - F51 Sustainable Energy Storage

Test # 1: Maximum power output

Purpose: To measure the amount of power that the system can supply instantaneously. The system should have the capacity to provide a larger output when necessary, but just for a shorter time period. This will determine what appliances the final design can power.

Scope: This test is a result of the flywheel and shaft design as well as the motor assembly. It will be measured in the output circuit.

Equipment: Multimeter, large resistor, power supply

Hazards: No danger of electrocution due to low power. The main hazard will be if the flywheel is unstable at high rpm.

PPE Requirements: Safety goggles if near the running flywheel.

Facility: Structure and composites lab.

Procedure:

1) Make sure PPE is on and strongfloor bolts are secure
2) Connect the resistor to the output terminal
3) Connect the multimeter in series to measure the current
4) Connect another multimeter in parallel across the resistor to measure voltage
5) Keep one tester next to Power Shutoff and one next to the Hand Brake, ready to stop test if there is anything unusual
6) Charge to 20 rpm and engage hand brake as safety test
7) Charge the flywheel to 250 rpm
8) Switch to discharge cycle.
9) Record output power at the beginning of the discharge cycle.

Results:

Trial	Voltage, V [V]	Output Power, P [W]
1		

Trial	Voltage, V [V]	Output Power, P [W]
2		

Trial	Voltage, V [V]	Output Power, P [W]
3		

It is desired that the flywheel will provide 15 W instantaneously.

This test will be repeated 3 times to reduce uncertainty

Numerical Analysis: Calculate output power by multiplying Current and Voltage. Determine uncertainty from multimeter and calculate error propagation in resultant output power.

Test Date(s):

Test Results:

Performed By:

Test Procedure - F51 Sustainable Energy Storage

Test #2 Sustained Power Output

Purpose: To measure the amount of time that the system can provide a typical power output for. This system needs to provide power for an extended amount of time. As the rpm decreases, an acceptable power output should still be possible. We will confirm this and measure the amount of time and energy.

Scope: This test is a result of the flywheel and shaft design as well as the motor assembly. It will be measured in the output circuit.

Equipment: Multimeter, timer, LED, power supply

Hazards: No danger of electrocution due to low power. The main hazard will be if the flywheel is unstable at high rpm.

PPE Requirements: Safety goggles should be worn whenever flywheel is running

Facility: Structure and composites lab.

Procedure:

1. Make sure all bolts are tight and PPE is worn
2. Connect the LED to the output terminal
3. Connect the multimeter in series to measure the current
4. Keep one tester next to Power Shutoff and one next to the Hand Brake, ready to stop test if there is anything unusual
5. Charge to 20 rpm and engage hand brake as safety test
6. Charge the flywheel to 250 rpm
7. Switch to discharge cycle.
8. Record output power every ten seconds until flywheel has stopped.

Results:

Time, *t* [s]	Output Power, *P* [W]
0	
10	
20	
30	

Time, *t* [s]	Output Power, *P* [W]
0	
10	
20	
30	

Time, *t* [s]	Output Power, *P* [W]
0	
10	
20	
30	

It is desired that the flywheel will provide .03 W for at least two minutes from 250 rpm.
This test will be repeated 3 times to reduce uncertainty

Test Date(s):
Test Results:

Performed By:

Test Procedure - F51 Sustainable Energy Storage

Test #3: Noise Measurement

Purpose: To determine the noise output of the entire system when run at high speeds

Scope: The tests the viability to have the system next to houses and in off grid locations where there is low noise pollution.

Equipment: Power supply, Decibel meter

Hazards: There are no immediate safety issues beyond typical precautions taken with the spinning system.

PPE Requirements: Safety Glasses

Facility: Structures and Composites Lab, Strongfloor

Procedure:

1. Make sure PPE is on and strongfloor bolts are secure
2. Connect power supply to motor and spin to maximum speed
3. Keep one tester next to Power Shutoff and one next to the Hand Brake, ready to stop test if there is anything unusual
4. Charge to 20 rpm and engage hand brake as safety test
5. As speed is increasing, take data points for every gain of 25 RPM
6. Take find decibel reading at maximum speed and record results

Results: Pass Criteria: The system is quieter than 30 dB

Fail Criteria: The system is louder than 30 dB

# of Samples: Three (3) Tests

Operating Speed	Test #1	Test #2	Test #3
25 RPM			
50 RPM			
75 RPM			
100 RPM			
125 RPM			
150 RPM			
175 RPM			
200 RPM			

Test Date(s):

Test Results:

Performed By:

Test Procedure - F51 Sustainable Energy Storage

Test #4: Power Loss

Purpose: To determine the total length of time that the system can dissipate charge to the load without any additional power

Scope: This test determines the entire functionality of the system, but pertains specifically to the performance of the bearing assembly

Equipment: Stopwatch

Hazards: There are no immediate safety issues beyond typical precautions taken with the spinning system.

PPE Requirements: Safety Glasses,

Facility: Mechanical Engineering Composites Lab, Strong Floor

Procedure:

1. Secure the Flywheel System to the Strong Floor using ½in T-nuts and the holes along the exterior of the flywheel system, and make sure PPE is on
2. Keep one tester next to Power Shutoff and one next to the Hand Brake, ready to stop test if there is anything unusual
3. Charge to 20 rpm and engage hand brake as safety test
4. Spin the system up to the operating speed of 250 RPM for 20 seconds
5. Disconnect the power supply whilst beginning a stopwatch timer
6. Once the flywheel stops spinning, stop the timer

Results: Pass Criteria: The Flywheel continues to spin beyond 30 minutes

Fail Criteria: The Flywheel spins fewer than 30 minutes

# of Samples: Three (3) Tests

	Test #1	Test #2	Test #3
Test Pass? (Y/N)			

Test Date(s):

Test Results:

Performed By:

Test Procedure - F51 Sustainable Energy Storage

Test #5: Storing Capacity

Purpose: To determine the total amount of energy that the prototype system can hold given our maximum RPM

Scope: This is testing the ability the flywheel assembly has to store energy.

Equipment: Load (LED), Multimeter, Stopwatch

Hazards: There are no immediate safety issues beyond typical precautions taken with the spinning system.

PPE Requirements: Make sure goggles are worn at all times when flywheel is in use

Facility: Structures and Composites Lab, Strongfloor

Procedure:

1. Make sure PPE is on and strongfloor bolts are secure
2. Connect Multimeter in series with load to measure current
3. Connect second multimeter in parallel with load to measure voltage
4. Keep one tester next to Power Shutoff and one next to the Hand Brake, ready to stop test if there is anything unusual
5. Charge to 20 rpm and engage hand brake as safety test
6. Fully spin up system to maximum velocity
7. Connect load to flywheel and start stopwatch
8. Take readings from multimeters every 2 seconds (to ensure constant power out)
9. Stop stopwatch once LED turns off
10. Record all data and calculate the total power output

Results: Pass Criteria: The Flywheel stores 100 J

Fail Criteria: The Flywheel stores less than 100 J

# of Samples: Three (3) Tests

Data:

Time, t [s]	Output Power, P [W]
0	
2	
4	
…	

Time, t [s]	Output Power, P [W]
0	
2	
4	
…	

Time, t [s]	Output Power, P [W]
0	
2	
4	
…	

Test Date(s):

Test Results:

Performed By:

Test Procedure - F51 Sustainable Energy Storage

Test #5: Storing Capacity

Purpose: To determine the total amount of energy that the prototype system can hold given our maximum RPM

Scope: This is testing the ability the flywheel assembly has to store energy.

Equipment: Load (LED), Multimeter, Stopwatch

Hazards: There are no immediate safety issues beyond typical precautions taken with the spinning system.

PPE Requirements: Make sure goggles are worn at all times when flywheel is in use

Facility: Structures and Composites Lab, Strongfloor

Procedure:

1. Make sure PPE is on and strongfloor bolts are secure
2. Connect Multimeter in series with load to measure current
3. Connect second multimeter in parallel with load to measure voltage
4. Keep one tester next to Power Shutoff and one next to the Hand Brake, ready to stop test if there is anything unusual
5. Charge to 20 rpm and engage hand brake as safety test
6. Fully spin up system to maximum velocity
7. Connect load to flywheel and start stopwatch
8. Take readings from multimeters every 2 seconds (to ensure constant power out)
9. Stop stopwatch once LED turns off
10. Record all data and calculate the total power output

Results: Pass Criteria: The Flywheel stores 100 J
Fail Criteria: The Flywheel stores less than 100 J
# of Samples: Three (3) Tests

Data:

Time, t [s]	Output Power, P [W]
0	
2	
4	
…	

Time, t [s]	Output Power, P [W]
0	
2	
4	
…	

Time, t [s]	Output Power, P [W]
0	
2	
4	
…	

Test Date(s):

Test Results:

Performed By:

Test Procedure - F51 Sustainable Energy Storage

Test #6: Charge Time
Purpose: To determine the total amount of time it takes the charge up the system to the maximum flywheel speed
Scope: This tests the motors ability to speed up the system in a given amount of time
Equipment: Power supply, stopwatch
Hazards: There are no immediate safety issues beyond typical precautions taken with the spinning system.
PPE Requirements: Wear safety goggles whenever the flywheel is running
Facility: Structures and Composites Lab, Strongfloor

Procedure:

1. Make sure all bolts are tight and PPE is worn
2. Connect power supply to motor and start stopwatch
3. Keep one tester next to Power Shutoff and one next to the Hand Brake, ready to stop test if there is anything unusual
4. Charge to 20 rpm and engage hand brake as safety test
5. Use tachometer to determine when maximum speed is reached
6. Stop stopwatch and record time

Results: Pass Criteria: The Flywheel stops within Five (5) minutes
Fail Criteria: The Flywheel continues to charge beyond Five (5) minutes
# of Samples: Three (3) Tests

Data:

Time, t [s]	Flywheel speed
0	
10	
20	
30	

Time, t [s]	Flywheel speed
0	
10	
20	
30	

Time, t [s]	Flywheel speed
0	
10	
20	
30	

Test Date(s):
Test Results:

Performed By:

Test Procedure - F51 Sustainable Energy Storage

Test #7: Brake Time
Purpose: To determine the total braking time of the system at varying rotational speeds
Scope: This test determines the entire functionality of the system, but pertains specifically to the performance of the braking assembly
Equipment: Stopwatch
Hazards: There are no immediate safety issues beyond typical precautions taken with the spinning system.
PPE Requirements: Safety Glasses
Facility: Mechanical Engineering Composites Lab, Strong Floor
Procedure:

1. Secure the Flywheel System to the Strong Floor using ½in T-nuts and the holes along the exterior of the flywheel system, and make sure PPE is on
2. Keep one tester next to Power Shutoff and one next to the Hand Brake, ready to stop test if there is anything unusual
3. Charge to 20 rpm and engage hand brake as safety test
4. Spin the system up to the operating speed of 250 RPM for 20 seconds
5. Disconnect the power supply
6. Apply the brake whilst beginning a stopwatch timer
7. Once the flywheel stops spinning, stop the timer

Results: Pass Criteria: The Flywheel stops within Five (5) seconds
Fail Criteria: The Flywheel continues to spin beyond Five (5) seconds
# of Samples: Three (3) Tests for 200 RPM

Operating Speed	Test #1	Test #2	Test #3
200 RPM			

Test Date(s):
Test Results:

Performed By:

Appendix R. DVPR

DVP&R - Design Verification Plan (& Report)											
Project:	F51 Sustainable Energy Storage		Sponsor:	Mr. Bhutani						Edit Date:	5/26/2021
TEST PLAN										TEST RESULTS	
Test #	Specification	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Parts Needed	Responsibility	TIMING		Numerical Results	Notes on Testing
								Start date	Finish date		
1	Maximum power output (1p)	Connect a maximum load at full charge and measure output	Output voltage and current	15 W	Multimeter	Final Prototype	Jack	5.24.21	5.24.21	Measured current and voltage, computed output power for each trial Appendix S	System reached a peak power of 35W, exceeding our initial expectations. This peak occured at the begining of the discharge cycle.
2	Sustained power output (2p)	Connect a typical load and measure output while recording time elapsed	Output voltage and current over time	.03 W	Multimeter	Final Prototype	Alyse	5.24.21	5.24.21	Measured voltage across resistor at 0.5 second intervals, computed output power Appendix S	The flywheel was able to keep a output over 0.03 W for the majority of the test. Values dipping below this threshold are dependent on trace spinning after the motor had hit its dissengagement limit.
3	Noise measurement (3p)	Run at maximum speed and record noise with a decibel meter	Maximum noise output (decibels)	Under 30 dB	Decibel meter	Final Prototype	Jake	5.21.21	5.21.21	Measured noise of environment then noise of system when operating for three trials 27.6, 28.1, 27.3 [dB]	System remained within limits of the maximum noise output. The process was difficult, as decibel outputs when combined do not add linearly, but rather concern the difference between sources.
4	Power loss (6p)	Fully charge and let discharge without any output load connected	Time till stopped (seconds)	30 min	Stopwatch	Final Prototype	Nick	5.24.21	5.24.21	Measured time to stop without discharging to a load Appendix S	System discharged slightly over 30 seconds, missing our goal signicantly. Much of this is attributed to the bearing losses and frictional elements in the system and our initial over-estimates for system performance. Ideally, the bearings would be magnetic or air-ride bearings so that friction can be kept to a minimum.

DVP&R - Design Verification Plan (& Report)

Project:	F51 Sustainable Energy Storage	Sponsor:	Mr. Bhutani	Edit Date:	5/26/2021

TEST PLAN / TEST RESULTS

Test #	Specification	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Parts Needed	Responsibility	TIMING Start date	TIMING Finish date	Numerical Results	Notes on Testing
5	Storing capacity (7p)	Fully charge, measure total power output until fully discharged	Output power (W) and length of time (seconds)	100 J	Stopwatch/ Multimeters	Final Prototype	Jack	5.24.21	5.24.21	Measured current and voltage at 0.5s time intervals, computed output power Appendix S	The System was able to output 211J of energy once set to discharge. This value could be larger if frictional components were not as influential.
6	Charge time (8p)	Start from stop, plug into charge controller for power, time in seconds the time to maximum RPM	Time (seconds)	5 minutes or less	Stopwatch	Final Prototype	Alyse	5.24.21	5.24.21	Data saved on computer program for flyhweel speeds in terms of time until max operating speed was reached Appendix S	The system is limited to certain charge up speeds as to not trip the motor drivers. The charge up speed is set at a constant rate around 1:50 minutes, although this rate can be changed.
7	Brake time (9p)	At 25%, 50% and 100% of maximum RPM, test braking time to complete stop	Time (seconds)	5 seconds or less	Stopwatch	Final Prototype	Nick	5.21.21	5.21.21	Recorded time it took for flywheel to come to a complete stop after brake was engaged Appendix S	The system was able to slow down within the 5 second benchmark for the lower listed speeds, but still required twice the amount of time for 100% of maximum RPM. This is due to the removal of our original brake. As it did fail, we would suggest redesigning the brake system to incoprorate a brake booster to gain a mechanical advantage, which would slow the system much faster and bring the flywheel to a stop in less than 5 seconds.

Appendix S. All test results.

Test 1: Maximum output power

Amp Data			Volt Data			
Time	Lapsed Time	Amperage	Time	Lapsed Time	Voltage	Wattage (W)
13.63	0.00	2.98	13.63	0.00	12.00	35.760

Test 2: Sustained power output

Trial 1:	Trial 2:	Trial 3:
20.15 seconds	21.17 seconds	22.63 seconds

Test 4: Power Loss

Trial 1:	Trial 2:	Trial 3:
32.2 seconds	31.62 seconds	31.87 seconds

Test 5: Storing Capacity

Amp Data		Volt Data		System Outputs	
Elapsed Time	Amperage	Elapsed Time	Voltage	Wattage (W)	Energy (J)
0.00	2.98	0.00	12.00	35.760	41.124
1.01	2.20	1.15	11.43	25.146	18.860
2.00	2.08	1.90	10.97	22.818	31.716
3.31	1.89	3.29	10.38	19.618	12.752
4.03	1.75	3.94	10.21	17.868	15.545
4.74	1.68	4.81	9.75	16.380	10.156
5.46	1.55	5.43	9.36	14.508	8.124
6.02	1.47	5.99	9.16	13.465	15.216
7.36	1.29	7.12	8.57	11.055	16.030
8.62	1.10	8.57	8.00	8.800	3.168
8.96	1.04	8.93	7.81	8.122	8.529
9.92	0.91	9.98	7.43	6.761	2.096
10.29	0.85	10.29	7.24	6.154	4.308
10.91	1.33	10.99	7.06	9.390	2.817
11.49	1.11	11.29	6.87	7.626	4.042
12.04	0.96	11.82	6.68	6.413	3.591
12.60	0.92	12.38	6.31	5.805	4.006

13.09	0.48	13.07	6.13	2.942	2.001
13.69	0.39	13.75	5.76	2.246	2.516
15.07	0.26	14.87	5.41	1.407	0.942
15.72	0.22	15.54	5.05	1.111	1.722
16.96	0.11	17.09	4.54	0.499	0.175
17.31	0.08	17.44	4.36	0.349	0.174
17.72	0.06	17.94	4.19	0.251	0.058
18.28	0.05	18.17	4.03	0.202	0.191
18.92	0.02	19.12	3.70	0.074	1.415

Total 244.771 211.273

Test 6: Charge Time

Trial 1:	Trial 2:	Trial 3:
150.2 seconds	150.7 seconds	150.8 seconds

Test 7: Brake Time

Operating Speed [rpm]	Time [s]
60	3.64
100	5.85
200	9.75
200	9.72
200	9.61

Average Brake Time @200 rpm: **9.69 seconds**

Appendix T. Uncertainty calculations and error propagation

UNCERTAINTY ANALYSIS FOR TEST 1

MEASURED QUANTITIES : CURRENT, I (A)
VOLTAGE, V (V)

COMPUTED QUANTITY : POWER, P = IV (W)

$$u_I = \sqrt{(B_I)^2 + (P_I)^2}$$

$B_I = \pm .008\ A$ (FROM MANUFACTURER)
$P_I = \pm .005\ A$

$$= \sqrt{(.008)^2 + (.005)^2} = \boxed{0.0094\ A}$$

$$u_V = \sqrt{(B_V)^2 + (P_V)^2}$$

$B_V = \pm .005\ V$
$P_V = \pm .005\ V$

$$= \sqrt{2(.005)^2} = \boxed{0.0071\ V}$$

$$P(X_m) = (2.98\ A)(12\ V) = 35.76\ W$$

$$P(I + u_I) = (2.98 + .0094A)(12\ V) = 35.87\ W$$

$$P(V + u_V) = (2.98\ A)(12 + .0071\ V) = 35.78\ W$$

$$s_I = P(I + u_I) - P(X_m) = 35.87 - 35.76\ W = 0.1132\ W$$

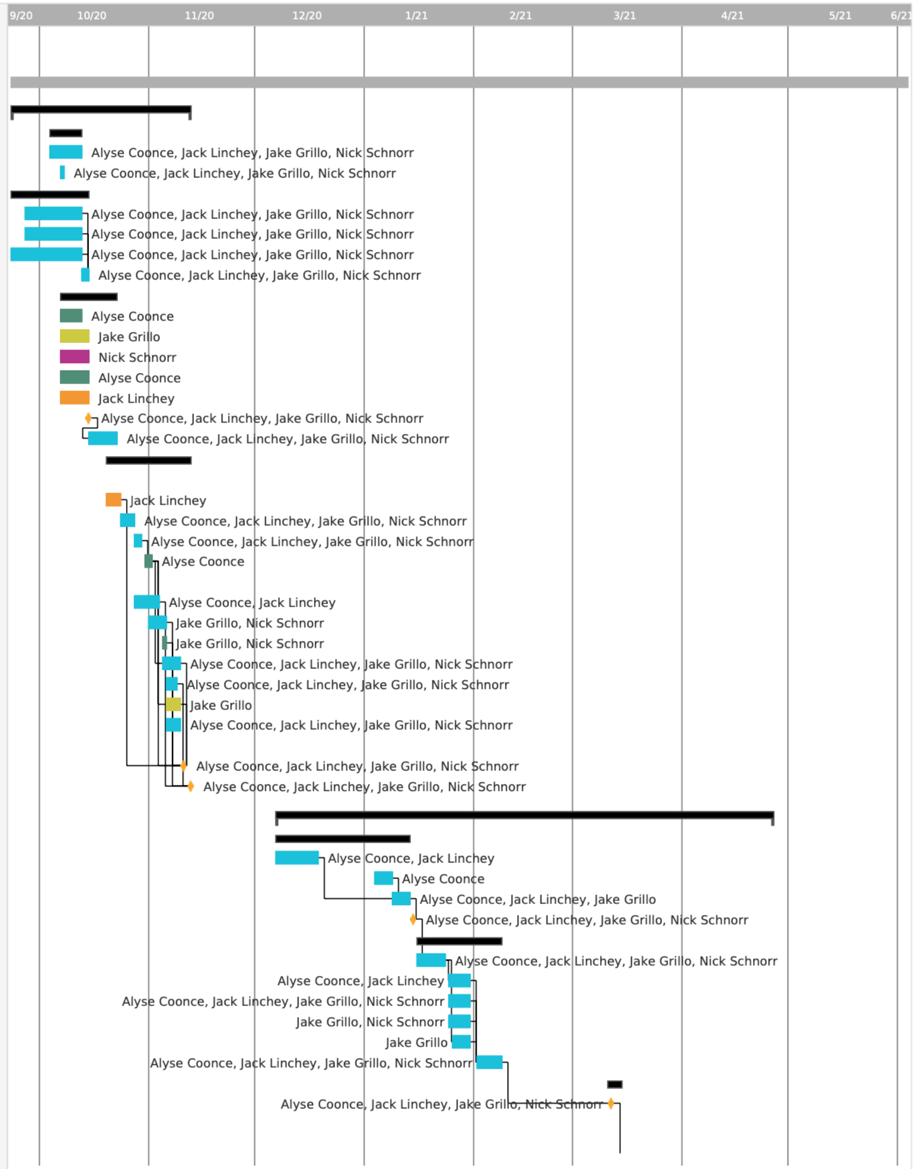
$$s_V = 35.78 - 35.76\ W = .0211\ W$$

$$u_P = \sqrt{s_I^2 + s_V^2} = \boxed{0.1152\ W}$$

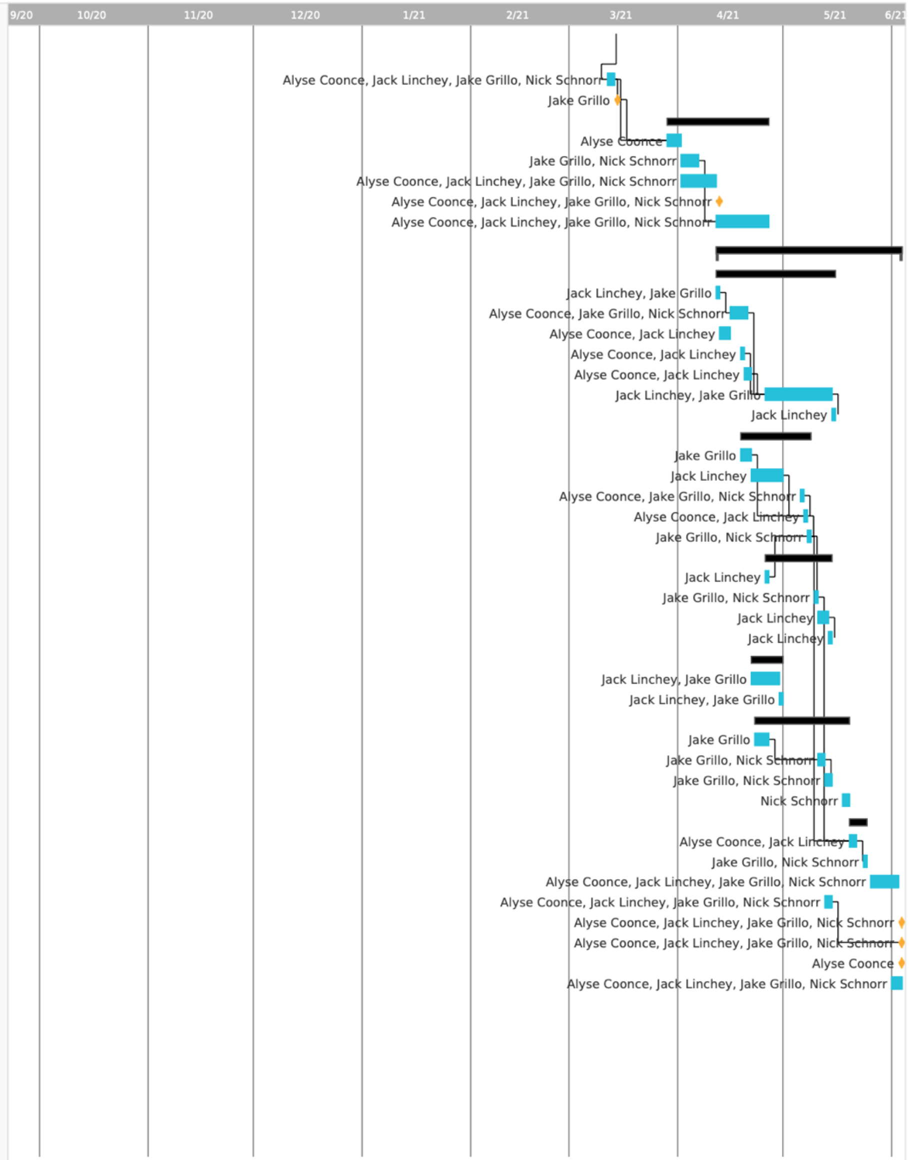
Current, I [A]	Voltage, V [V]	Current Uncertainty, u_I	Voltage Uncertainty, u_V	Computed Power, P [W]	Computed Power with Current Uncertainty [W]	Computed Power with Voltage Uncertainty [W]	Sensitivity to Current, s_I	Sensitivity to Voltage s_V	Power Uncertainty, u_P
2.98	12	0.0094	0.0071	35.76	35.87	35.78	0.1132	0.0211	0.1152

Appendix U. Gantt chart

F51 - Sustainable Energy St...	start	end	0h	100%
Fall Quarter	**09/23/20**	**11/12/20**	**0h**	**100%**
Problem Statement	**10/04/20**	**10/12/20**	**0h**	**100%**
Problem Statement	10/04	10/12	0	100%
Sponsor/Faculty Interviews	10/07	10/07	0	100%
QFD House of Quality	**09/23/20**	**10/14/20**	**0h**	**100%**
Patent Search	09/27	10/12	0	100%
Search Previous Designs	09/27	10/12	0	100%
Research Applicable Technologies	09/23	10/12	0	100%
QFD Complete	10/13	10/14	0	100%
Scope of Work	**10/07/20**	**10/22/20**	**0h**	**100%**
Boundary Diagram	10/07	10/12	0	100%
Background Info	10/07	10/14	0	100%
Objectives	10/07	10/14	0	100%
Customer Requirements Table	10/07	10/14	0	100%
Project Management	10/07	10/14	0	100%
Draft SOW	10/14	10/14	0	100%
SOW edited and sent to sponsor	10/15	10/22	0	100%
PDR	**10/20/20**	**11/12/20**	**0h**	**100%**
PDR Ideation	**-**	**-**	**0h**	**0%**
Ideation Session	10/20	10/23	0	100%
Develop Function Pugh Matrices	10/24	10/27	0	100%
Create Morphological Matrix	10/28	10/29	0	100%
Evaluate and Select Idea	10/31	11/01	0	100%
PDR Preparation	**-**	**-**	**0h**	**0%**
Edit Scope of Work from Feedback	10/28	11/03	0	100%
Write Concept Design Chapter	11/01	11/05	0	100%
Meet with EE Professor	11/05	11/05	0	100%
Build Concept Design Prototype	11/05	11/09	0	100%
Apply Changes from Peer Review in...	11/06	11/08	0	100%
CAD Model	11/06	11/09	0	100%
Prepare Presentation	11/06	11/09	0	100%
PDR	**-**	**-**	**0h**	**0%**
PDR Presentation	11/10	11/10	0	100%
PDR Report	11/12	11/12	0	100%
Winter Quarter	**12/07/20**	**04/26/21**	**0h**	**100%**
Estimate Friction Losses	**12/07/20**	**01/13/21**	**0h**	**100%**
Reach out to 3 Bearing Manufactur...	12/07	12/18	0	100%
Contact Fluids Professors on Rotor...	01/04	01/08	0	100%
Execute Design Calcs for Feasability	01/09	01/13	0	100%
Interim Design Review	01/14	01/14	0	100%
Prep for CDR	**01/16/21**	**02/08/21**	**0h**	**100%**
Build Structural Prototype	01/16	01/23	0	100%
Finalize Bearing Selection	01/25	01/30	0	100%
Finalize Flywheel Cross-Section Des...	01/25	01/30	0	100%
Finalize Motor Choice	01/25	01/30	0	100%
Detailed CAD (Manufacturing Plan)	01/26	01/30	0	100%
Prep CDR Report	02/02	02/08	0	100%
CDR	**03/11/21**	**03/14/21**	**0h**	**100%**
Critical Design Review Presentation	03/11	03/11	0	100%



Edit CDR from Feedback	03/12	03/13	0	100%
Submit CDR to Sponsor	03/14	03/14	0	100%
Manufacturing	**03/29/21**	**04/26/21**	**0h**	**100%**
Risk Assessment/Safety Review	03/29	04/01	0	100%
Order Parts	04/02	04/06	0	100%
Experimental Design/Testing Plan	04/02	04/11	0	100%
Manufacturing and Test Review	04/12	04/12	0	100%
Manufacturing	04/12	04/26	0	100%
Spring Quarter	**04/12/21**	**06/03/21**	**0h**	**100%**
Manufacturing - Chassis	**04/12/21**	**05/15/21**	**0h**	**100%**
Cut Frame bars to length	04/12	04/12	0	100%
Grind Frame Bar ends	04/16	04/20	0	100%
Drill Frame Bars	04/13	04/15	0	100%
Cut Side Panels to length	04/19	04/19	0	100%
Cut and Drill Angle Iron	04/20	04/21	0	100%
Weld Chassis Assembly	04/26	05/14	0	100%
Weld Side Panels	05/15	05/15	0	100%
Manufacturing - Flywheel	**04/19/21**	**05/08/21**	**0h**	**100%**
Machine Shaft	04/19	04/21	0	100%
Machine Flywheel	04/22	04/30	0	100%
Broach Flywheel	05/06	05/06	0	100%
Attach Shaft to Flywheel	05/07	05/07	0	100%
Complete Flywheel Assembly	05/08	05/08	0	100%
Manufacturing - Braking	**04/26/21**	**05/14/21**	**0h**	**100%**
Machine Brake Rotor Spacer	04/26	04/26	0	100%
Attach Brake Rotor to Flywheel Ass...	05/10	05/10	0	100%
Mount Handbrake Assem.	05/11	05/13	0	100%
Connect hydraulic lines	05/14	05/14	0	100%
Manufacturing - Bearings	**04/22/21**	**04/30/21**	**0h**	**100%**
Machine Thrust Bearing Housing	04/22	04/29	0	100%
Complete Bearing Assemblies	04/30	04/30	0	100%
Manufacturing - Motor/Electronics	**04/23/21**	**05/19/21**	**0h**	**100%**
Cut Motor Mount	04/23	04/26	0	100%
Weld Crossbeam & Motor Mount	05/11	05/12	0	100%
Assemble Motor Assembly	05/13	05/14	0	100%
Package Electronics in Housing	05/18	05/19	0	100%
Testing	**05/20/21**	**05/24/21**	**0h**	**100%**
Tests 1, 2 & 3	05/20	05/21	0	100%
Tests 4, 5, 6 & 7	05/24	05/24	0	100%
Expo Poster	05/26	06/02	0	100%
Operators Manual	05/13	05/14	0	100%
Finish FDR	06/03	06/03	0	100%
Expo	06/03	06/03	0	100%
Submit FDR to Sponsor	06/03	06/03	0	100%
Clean Up	06/01	06/03	0	100%



Appendix V. FMEA

												Action Results			
System / Function	**Potential Failure Mode**	**Potential Effects of the Failure Mode**	**Severity**	**Potential Causes of the Failure Mode**	**Current Preventative Activities**	**Occurence**	**Current Detection Activities**	**Detection**	**Priority**	**Recommended Action(s)**	**Responsibility & Target Completion Date**	**Actions Taken**	**Severity**	**Occurence**	**Criticality**
Flywheel System / Function correctly and safely at max speed	Flywheel ruptures	user introduced to possible harm while system is functioning	10	1) Unbalanced Mass due to impure casting process 2) Detaches from shaft 3) Hits resonant frequency at operating speeds	1) From trusted vendor/testing 2) Make sure welds up to needed strength 3) Vibes analysis	5	-run flywheel at max speed for duration of time -calculate resonant frequency as cross section design evolves	4	200	Perform plenty of analysis on the designed shape of the flywheel; research shapes already used in production to ensure safe operation	February 2021	Decided upon simple shape of flywheel, running flywheel at dramatically lowered speeds than originally anticipated			
Flywheel System / Meets customer requirements	Materials used not systainable	materials are toxic to mine/manufacture/recycle	5	1) Misinformation from sourcing materials	1) Used trusted vendor	1	-ensure proper material used	1	5						
	Materials cannot be procured		4	1) No vendors to sell desired materials 2) Price too high	1) Do thorough research into vendors 2) If too expensive can change material	1	-ensure proper material used	1	4						
Support System / Minimizes frictional losses	Bearings create excessive heat	a) can't hold charge for long enough b) doesn't store enough power c) creates high losses	5	1) Experience larger than anticipated loads 2) loses lubrication over short operation	1) Use a significant design factor 2) Achieve low heat loss	8	-heat transfer analysis of bearings -pick bearings with low frictional losses	3	120	Design ideal system with magnetic bearings; for protoype/scale model, need to use ball bearings due to pricing and availability; perform tests in order to compare scale model to ideal model	February 2021	Ran analysis on how much frictional losses would occur with all three bearings			
	Vacuum chamber can't completely expel the air/leak	a) can't hold charge for long enough b) doesn't store enough power c) creates high losses	5	1) Sealant cracks or becomes useless 2) Weather conditions corrode exterior 3) Pump Failure/ not sized for volume of container correctly 4)Welds break	1) All--weather sealant 2) Pump/fluids Analysis 3) Necessary weld analysis	8	-submerge in water, see how much leaks into system -test for rust	2	80						
Support System / Strength to support flywheel and components	Failure due to yielding	a) system breaks b) user introduced to possible harm	10	1) Bends due to mass distribution in flywheel 2) Hits resonant frequency at operating speeds 3) Unbalanced mass due to impure casting process	1) Test flywheel for even mass distribution 2) Vibes analysis 3) Test flywheel for even mass distribution	7	- Implementing of dial gage on both axle and rotor - Listening for rythmic patterns - Inspecting bearing wear / condition	4	280	Ample analysis and generous design factors must be considered in the designing of the shaft. Additionally, Vibration analysis on the selected material will be required to avoid the resonant speeds. Before assembly, machining must be done to ensure the most balanced mass possible.	February 2021	Ran FEA on shaft diameter as well as the seat the flywheel sits on; not able to actually balance the mass, but took extra care to find the flywheels center as well as humanky possible			

												Action Results			
System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurence	Current Detection Activities	Detection	Priority	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken	Severity	Occurence	Criticality
Support System / Align elements	Failure due to cracks/fatigue	a) system breaks b) user introduced to possible harm	10	1) Reversed loading if orientated sideways	1) Orient vertically	6	- Visual inspection for cracks	5	300	Align shaft with multiple bearings to ensure minimized moments along the rotor. Encase rotor in protective coating to bind its contents i nthe event of cracking	April 2021	Due to variability and possible mistakes during welded, we waited to drill the holes for the top bearing housing until we could half assemble the prototype. This insured proper vertical alignment of the shaft and all its components			
	Shaft could flex too much	a) system breaks b) user introduced to possible harm	8	1) Design for strength and not stiffness 2) Materials wear if in contant over time	1) stress analysis 2) fatigue strength	7	- Visually inspect Bearings - Analyze friction losses over time	3	168	Do multiple test trials at lower speeds to check for wear and increased friction losses. Align shaft with multiple bearings	May 2021	Plan to test at much lower speed (200rpm)			
	Shaft could break	a) system breaks b) user introduced to possible harm	10	1) Reversed loading if orientated sideways 2) Spin of earth could induce moment on shaft 3) Safety shut down could be too violent	1) Orient vertically 2) Take induced moment into account 3) Safety shut down analysis	6	- Visually Inspect shaft - Dial gauge to determine runout	4	240	Align Shaft with multiple bearings to ensure minimized moments. Consider hardening the shaft to increase strength, although it loses ductility in the process	April 2021	Due to variability and possible mistakes during welded, we waited to drill the holes for the top bearing housing until we could half assemble the prototype. This insured proper vertical alignment of the shaft and all its components			
Braking System / Slow/stop rotation of flywheel	Damage flywheel drum beyond repair	a) doesn't store enough power b) user introduced to possible harm c) can't hold charge for long enough	9	1) Brake lines burst under vacuum 2) Seals of cylinders fail due to use 3) Caliper becomes misalligned	1) Brake line analysis 2) Weld analysis 3) Periodic inspections	2	- Visual inspection of welds, pressure gauge, and brake lines - Full testing of system from maximum to full stop	2	36						
	Not able to slow down flywheel within a small enough time window	user introduced to possible harm	9	1) Brake Caliper unable to apply enough braking force 2) Brake pads are worn 3) Flywheel is misaligned with braking system	1) Brake safety analysis 2) Periodic inspections 3) Tight tolerance on assembly	3	- Brake Preliminary Testing - Reviews of stock brake systems	5	135	Possibly have back up fail safe systems in place in case the standard brakes can't work fast enough.	March 2021	Have both hand brake and the braking capability of the motor			
	Doesn't immediately engage when user commands	a) does not respond to inputs b) user introduced ot possibl eharm	9	1) Brake Booster / Master cylinder is underpressurized 2) Brake-by-wire system has too low of refresh rate	1) Periodic inspections 2) Analysis of brake-by-wire system	3	- Test reaction time pre-implementation	2	54						

												Action Results			
System / Function	**Potential Failure Mode**	**Potential Effects of the Failure Mode**	**Severity**	**Potential Causes of the Failure Mode**	**Current Preventative Activities**	**Occurence**	**Current Detection Activities**	**Detection**	**Priority**	**Recommended Action(s)**	**Responsibility & Target Completion Date**	**Actions Taken**	**Severity**	**Occurence**	**Criticality**
Power accpetance/Delivery system / Adjusts speed of flywheel	can't charge as fast as solar panel produces power	User will experience decreased power supply	6	1) Undersized Charge controller 2) Flywheel reaches maximum speed	1) Controller Analysis 2) Max storage analysis	4	- test for charge controller overload - test for max safe charging speed	4	96						
Power accpetance/Delivery system / Ability to change frequency	stator of machine contacts the rotor	a) Reduced efficiency b) Damage on machine	10	1) Misalignment of motor 2) Flywheel axle comes out of alignment with bearings	1) Tight tolerance on assembly 2) Periodic inspections	5	- Test for max deflection of rotor shaft - post assembly tolerancing inspection	7	350	Procure machine with slightly larger air gap between stator and rotor that is compatable with shaft.	February 2021	Was able to find correct machine			
Containment System / Protects internal systems and flywheel	Motion within chamber induces moment and rolls housing	user introduced to possible harm	10	1) Flywheel loads are too high for system 2) Chamber is not bolted to ground or surface	1) Support system analysis 2) Mounting analysis	5	- if movement occurs system shut down needed	2	100	Make sure housing is bolted down, or entire assembly is buried underground	March 2021	Welded tabs onto siding tat could be bolted down onto the Strong Floor			
Containment System / Encased chamber maintains vacuum pressure	pressure warps chamber	system introduced to environment/extreme weather conditions	9	1) Vacuum is too high 2) Chamber Walls are too thin	1) Use a pressure control vacuum system 2) Calculate allowable pressure tolerance of housing	4	Alarm if pressure sensor out of expected range	2	72						
	Vacuum seal is not maintained	a) creates higher losses b) system introduced to environment/extreme weather conditions	8	1) Pressure Valve is unseated 2) Weld Layers separate and crack	1) Regular inspection before use	3	Alarm if pressure sensor out of expected range	2	48						
Control System / Manages Inputs	Component disconnected	a) Inputs are not received b) Inputs are not handled correctly	8	1) Solder breaks 2) Wire disconnected from breadboard or Arduino	1) Test all wire connections 2) Use proper header pins 3) Organize wiring	5	Test connections with Arduino regularly	3	120	Create a housing for the electronic components so that they will not be touched	April 2021	Plastic box as well as 3D printed control box			
	Input connection lost	Stimulus from given component will not be registered	6	1) Arduino loses power 2) Input component fails	1) Add low power indicator 2) Use electrostatic discharge protection	5	Test connections with Arduino regularly	3	90	Use proper testing and routines for failure management	May 2021	Using the Strong Floor with extended wires for the control box to ensuresafe distance and secure testing conditions			
Control System / Displays outputs	Display fails	a) User will not be able to view the current charge b) User will not be able to view the current output c) User will not be able to view the current flywheel speed	5	1) LCD fails 2) Bug in code 3) Tachometer innacurate	1) Operate LCD according to datasheet requirements 2) Thoroughly test code, add verbose debugging option	4	Observation of LCD	1	20						

												Action Results			
System / Function	**Potential Failure Mode**	**Potential Effects of the Failure Mode**	**Severity**	**Potential Causes of the Failure Mode**	**Current Preventative Activities**	**Occurence**	**Current Detection Activities**	**Detection**	**Priority**	**Recommended Action(s)**	**Responsibility & Target Completion Date**	**Actions Taken**	**Severity**	**Occurence**	**Criticality**
Control System / logs data	Data logging connection lost	History data will be lost	7	1) SSH times out 2) Wi-Fi chip fails	1) Send message at least every 30 min 2) Use electrostatic discharge protective housing	5	Observation of dataflow. Interrupt if no data received in a given amount of time	1	35						
	Bad transfer of data	a) History data will be inaccurate b) History data will be deleted	5	1) Packet loss 2) Buffer overflow	1) Use checksum 2) Send in proper lengths	3	Sending data at regular intervals to detect any losses	1	15						

Appendix W. Risk Assessment

designsafe Report

Application: F51 Energy Storage
Description: The flywheel
Product Identifier:
Assessment Type: Detailed
Limits:
Sources:
Risk Scoring System: ANSI B11.0 (TR3) Two Factor

Analyst Name(s):
Company:
Facility Location:

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-1-1	Passerbys Walk nearby	electrical / electronic : energized equipment / live parts Motor could arc to undesireable location	Serious Unlikely	Medium		Serious		
1-1-2	Passerbys Walk nearby	electrical / electronic : water / wet locations Live wires could short system in water	Serious Unlikely	Medium		Serious		
1-1-3	Passerbys Walk nearby	fire and explosions : sparks Faulity Wiring	Serious Remote	Low		Serious		
1-1-4	Passerbys Walk nearby	noise / vibration : noise / sound levels > 80 dBA Bearing cause excessive noise at high speeds	Moderate Likely	Medium		Moderate		
1-1-5	Passerbys Walk nearby	fluid / pressure : explosion / implosion Rupture of flywheel	Catastrophic Unlikely	Medium	Use steel siding and cage, kill switch close by	Catastrophic Unlikely	Medium	
1-2-1	Passerbys Operating Construction equipment	mechanical : drawing-in / trapping / entanglement Loose wiring or rotating exposed parts left uncovered	Serious Unlikely	Medium		Serious		
1-2-2	Passerbys Operating Construction equipment	electrical / electronic : energized equipment / live parts System is producing electricity	Serious Unlikely	Medium		Serious		

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-2-3	Passerbys Operating Construction equipment	electrical / electronic : water / wet locations Shorts with standing water	Serious Unlikely	Medium		Serious		
1-2-4	Passerbys Operating Construction equipment	fire and explosions : sparks Faulity wiring	Serious Remote	Low		Serious		
2-1-1	Consumers Connect System to Solar	mechanical : pinch point Wire pinch	Moderate Remote	Negligible		Moderate		
2-1-2	Consumers Connect System to Solar	mechanical : unexpected start If System left on	Serious Unlikely	Medium		Serious		
2-1-3	Consumers Connect System to Solar	electrical / electronic : energized equipment / live parts	Serious Unlikely	Medium		Serious		
2-1-4	Consumers Connect System to Solar	electrical / electronic : shorts / arcing / sparking uninsulated wire	Serious Remote	Low		Serious		
2-1-5	Consumers Connect System to Solar	electrical / electronic : improper wiring Wiring done poorly	Serious Remote	Low		Serious		
2-1-6	Consumers Connect System to Solar	electrical / electronic : water / wet locations If system isn't water tight	Catastrophic Unlikely	Medium	Avoid wet conditions for testing/protoype	Catastrophic Remote	Low	
2-1-7	Consumers Connect System to Solar	electrical / electronic : power supply interruption Clouds	Moderate Unlikely	Low		Moderate		

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
2-2-1	Consumers Consume power from system	mechanical : pinch point connecting to output	Serious Remote	Low		Serious		
2-2-2	Consumers Consume power from system	mechanical : product instability unreliable charging	Moderate Unlikely	Low		Moderate		
2-2-3	Consumers Consume power from system	electrical / electronic : energized equipment / live parts output should be treated as outlet	Serious Unlikely	Medium		Serious		
2-2-4	Consumers Consume power from system	electrical / electronic : lack of grounding (earthing or neutral) connected component destroyed	Serious Remote	Low		Serious		
2-2-5	Consumers Consume power from system	noise / vibration : noise / sound levels > 80 dBA bearings have high losses	Serious Likely	High	Rubber isolators, high amount of lubrication, soundproofing if necessary	Serious Unlikely	Medium	All
2-3-1	Consumers Periodic Check-up	mechanical : drawing-in / trapping / entanglement if opened while system not discharged	Catastrophic Unlikely	Medium	Alarm goes off if opened while running	Catastrophic Unlikely	Medium	
2-3-2	Consumers Periodic Check-up	mechanical : pinch point opening system	Serious Unlikely	Medium		Serious		
2-3-3	Consumers Periodic Check-up	electrical / electronic : shorts / arcing / sparking electrocution	Serious Unlikely	Medium		Serious		

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
2-4-1	Consumers Activate emergency brake system	mechanical : product instability	Serious Likely	High	Ensure a clean brake fluid system, implement a computer controlled brake with hall sensor, limit human interference	Serious Remote	Low	All
2-5-1	Consumers Clean Exterior of System	mechanical : cutting / severing sharp edges	Moderate Likely	Medium		Moderate		
2-5-2	Consumers Clean Exterior of System	mechanical : drawing-in / trapping / entanglement cleaning while engaged	Catastrophic Unlikely	Medium	Alarm goes off if opened while running	Catastrophic Remote	Low	
2-5-3	Consumers Clean Exterior of System	electrical / electronic : shorts / arcing / sparking cleaning/disconnecting	Serious Unlikely	Medium		Serious		
2-5-4	Consumers Clean Exterior of System	fire and explosions : hot surfaces friction	Moderate Unlikely	Low		Moderate		
3-1-1	Testing Team Monitor control systems	mechanical : unexpected start someone presses the wrong button	Moderate Likely	Medium		Moderate		
3-1-2	Testing Team Monitor control systems	electrical / electronic : energized equipment / live parts electrocution	Serious Unlikely	Medium		Serious		
3-2-1	Testing Team Confirm flywheel balance	mechanical : product instability misalignment during manufacturing	Serious Unlikely	Medium		Serious		

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
3-2-2	Testing Team Confirm flywheel balance	noise / vibration : product / equipment damage rupture due to high vibration	Catastrophic Likely	High	Rubber isolators for the bearings to seat onto the frame, machine flywheel carefully to ensure complete balance	Catastrophic Unlikely	Medium	All
3-3-1	Testing Team Remove/Install side panels	mechanical : crushing hands crushed	Catastrophic Remote	Low		Catastrophic		
3-3-2	Testing Team Remove/Install side panels	mechanical : pinch point	Moderate Remote	Negligible		Moderate		
3-4-1	Testing Team Power on and off	electrical / electronic : energized equipment / live parts energy left in system after discharging wheel	Moderate Likely	Medium		Moderate		
3-4-2	Testing Team Power on and off	electrical / electronic : power supply interruption braking or fully discharging	Serious Unlikely	Medium		Serious		
3-5-1	Testing Team Lubricate bearings	mechanical : pinch point pinched between bearings	Serious Remote	Low		Serious		
3-5-2	Testing Team Lubricate bearings	fire and explosions : flammable liquid / vapor lube fire	Serious Remote	Low		Serious		
3-6-1	Testing Team Perform noise tests	noise / vibration : noise / sound levels > 80 dBA too noisy	Moderate Likely	Medium		Moderate		

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
3-6-2	Testing Team Perform noise tests	noise / vibration : loss of hearing acuteness need earplugs	Moderate Unlikely	Low		Moderate		
3-7-1	Testing Team Perform energy strorage time tests	electrical / electronic : energized equipment / live parts electrocution while measuring output	Moderate Unlikely	Low		Moderate		
3-7-2	Testing Team Perform energy strorage time tests	electrical / electronic : power supply interruption disharges fully	Minor Remote	Negligible		Minor		